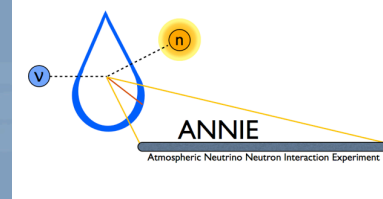# Expression of Interest:
Atmospheric Neutrino Neutron Interaction Experiment

Matt Wetstein
Enrico Fermi Institute, University of Chicago
Argonne National Laboratory

on behalf of the ANNIE Collaboration:

I. Anghel[1,4], G. Davies[4], F. Di Lodovico[11], A. Elagin[9], H. Frisch[9], R. Hill[9], G. Jocher[5], T. Katori[11], J. Learned[11], R. Northrop[9], C. Pilcher[9], E. Ramberg[3], M.C. Sanchez[1,4], M. Smy[7], H. Sobel[7], R. Svoboda[6], S. Usman[5], M. Vagins[7], G. Varner[10], R. Wagner[1], M. Wetstein[9], L. Winslow[8], and M. Yeh[2]

[1]Argonne National Laboratory   [2]Brookhaven National Laboratory   [3]Fermi National Accelerator Laboratory   [4]Iowa State University
[5]National Geospatial-Intelligence Agency   [6]University of California at Davis   [7]University of California at Irvine
[8]University of California at Los Angeles   [9]University of Chicago [10]University of Hawaii   [11]Queen Mary University of London

Fermilab PAC Meeting
January 22, 2014

U.S. DEPARTMENT OF ENERGY

ANNIE
Atmospheric Neutrino Neutron Interaction Experiment

- A measurement of the abundance of final state neutrons from neutrino interactions in water, as a function of energy.
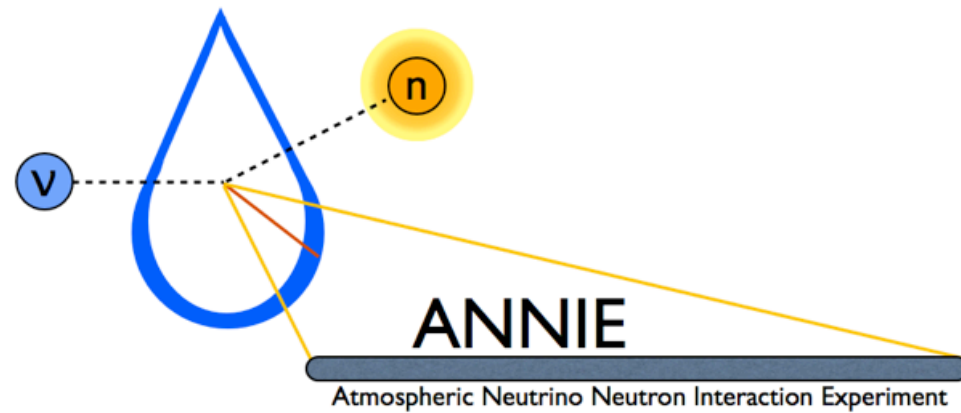
a key measurement for proton decay physics, supernova neutrino detection in water, and fundamental neutrino interaction physics


first 2 radiation lengths of a 1.5 GeV $\pi^0 \rightarrow \gamma\gamma$

reconstructed
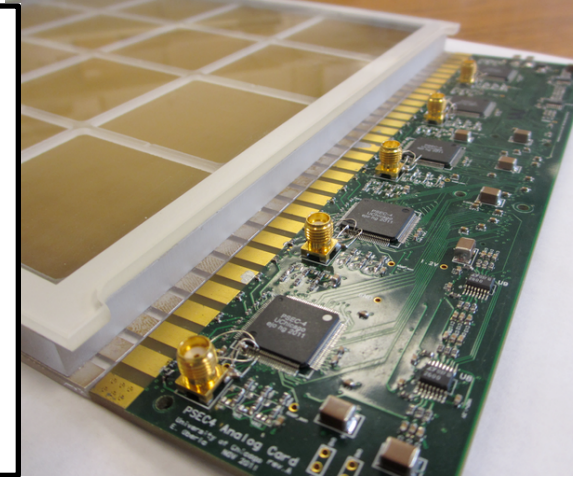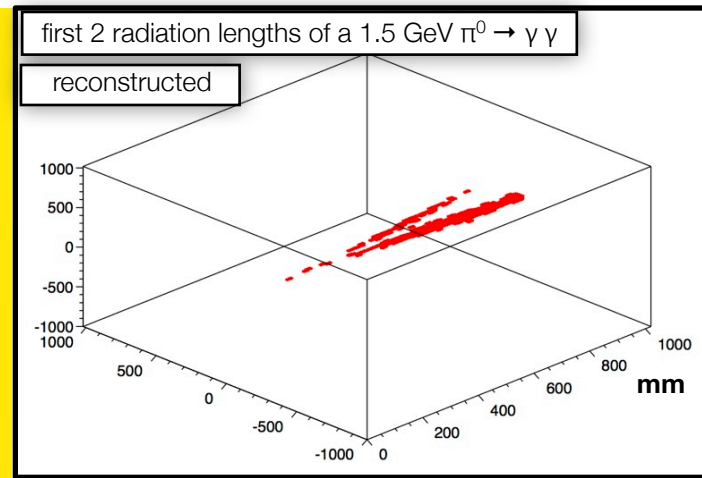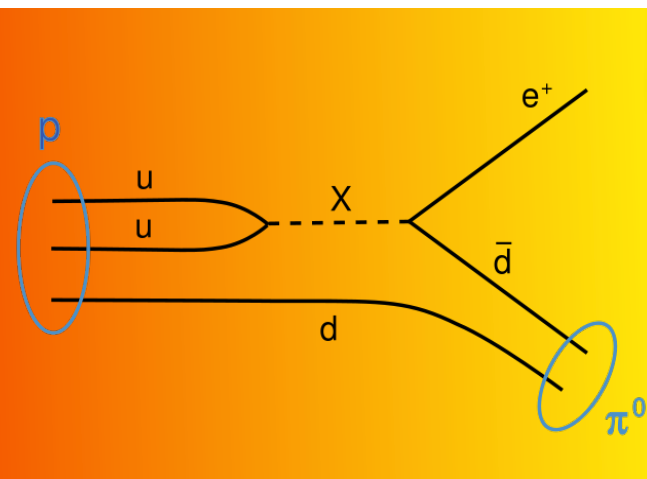
- Demonstration of a new approach to neutrino detection: *Optical Time Projection Chamber* using new photosensor technology.

Proton decay (PDK) searches in planned megaton-scale water Cherenkov detectors such as Hyper-K could achieve unprecedented sensitivity.
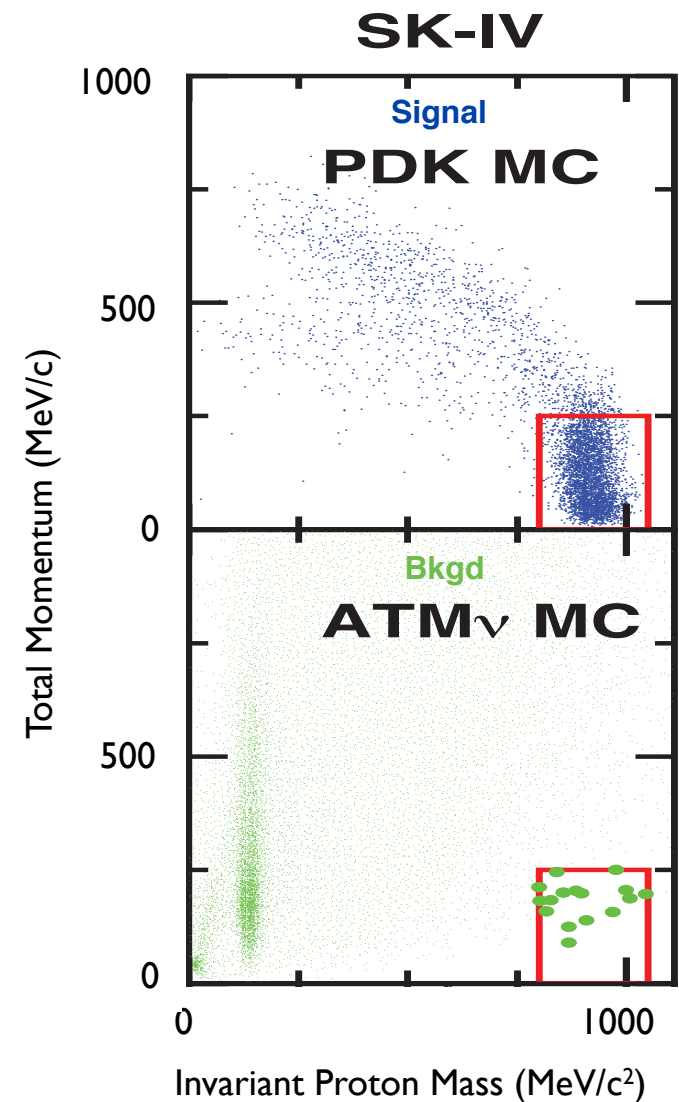
However, at such scales, previously negligible backgrounds from atmospheric neutrinos start to limit this sensitivity.

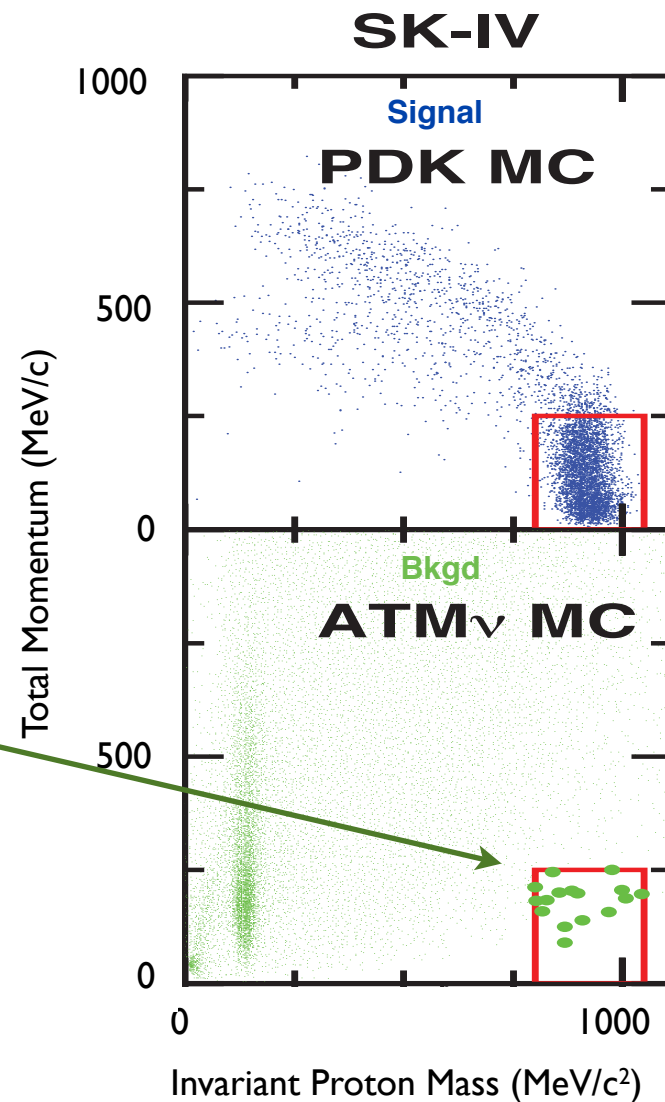Techniques capable of reducing these backgrounds would have a large impact on the potential physics reach.
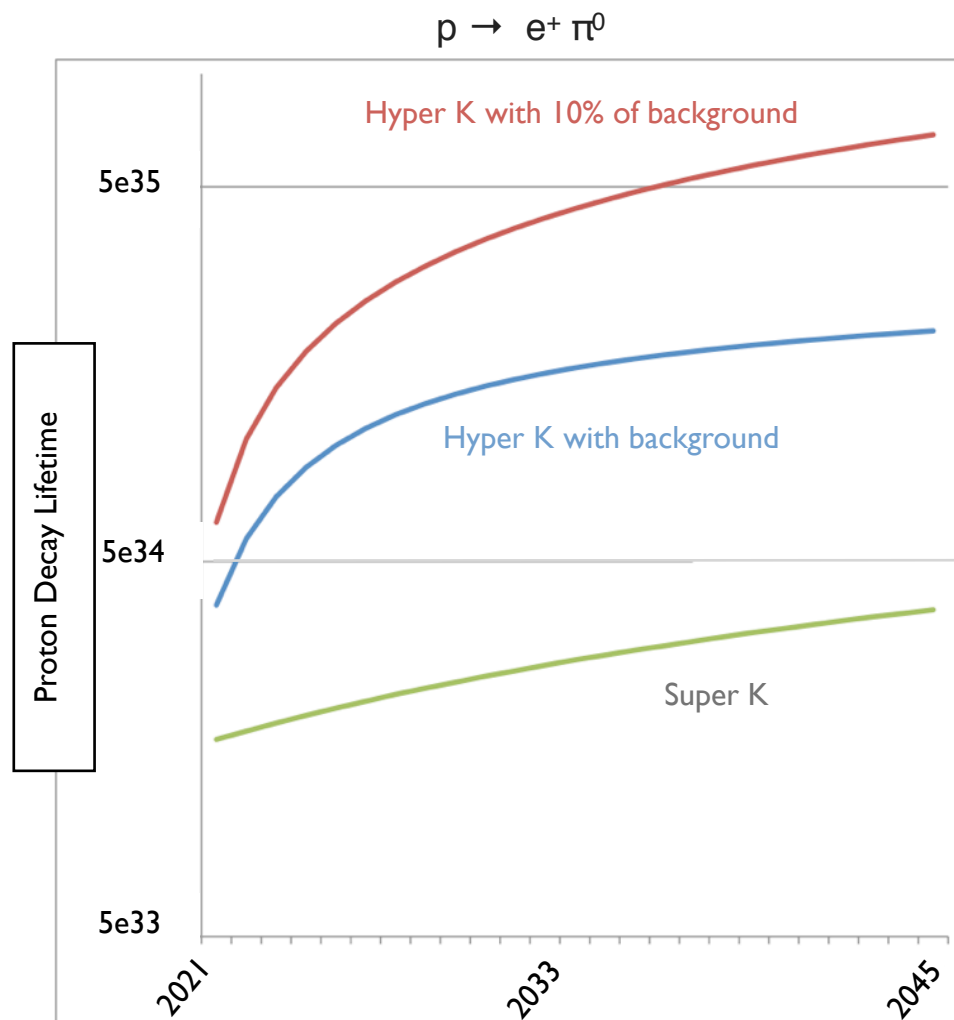
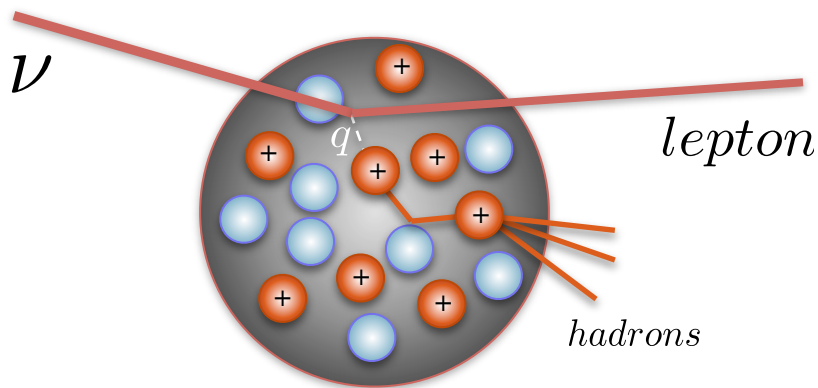$p \rightarrow e^+ \pi^0$

Backgrounds come almost exclusively
from atmospheric neutrino interactions.

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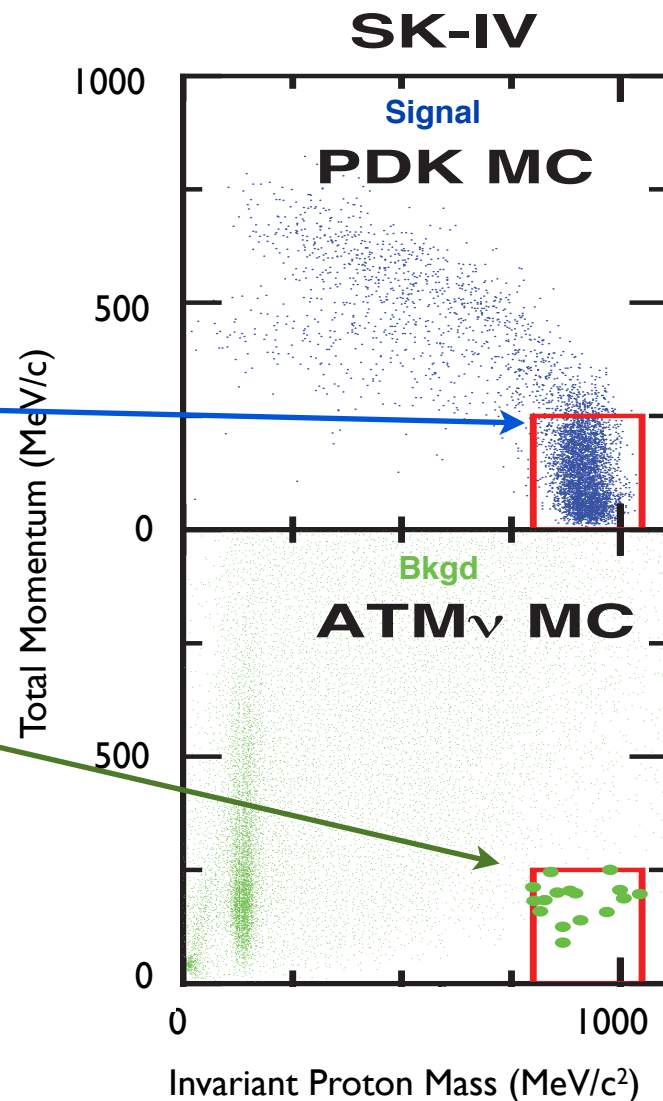High energy neutrino interactions typically produce neutrons in the final state.
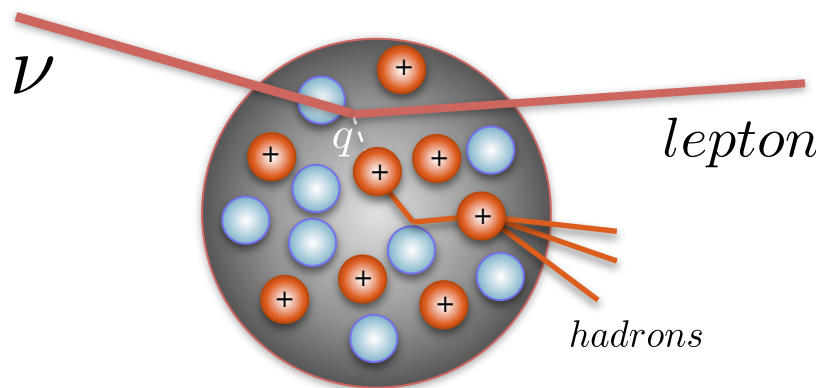
ν

q

lepton

hadrons

SK-IV

Signal

PDK MC

Total Momentum (MeV/c)

1000

500

0

Bkgd

ATMν MC

500

0

0   1000

Invariant Proton Mass (MeV/c²)

Backgrounds come almost exclusively
from atmospheric neutrino interactions

Proton decay events are expected to only
rarely produce neutrons in the final state.

High energy neutrino interactions typically
produce neutrons in the final state

ν

q

$lepton$

$hadrons$

SK-IV

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PDK MC

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0   1000

Invariant Proton Mass (MeV/c²)

Backgrounds come almost exclusively from atmospheric neutrino interactions.

Proton decay events are expected to only rarely produce neutrons in the final state.

High energy neutrino interactions typically produce neutrons in the final state.

Thus, neutron-tagging in large Water Cherenkov detectors would provide a handle for separating between signal and background.

Efficient neutron-tagging can be achieved by dissolving Gadolinium salts in water. Gd has a high neutron capture cross-section and the captures release 8 MeV in gammas.
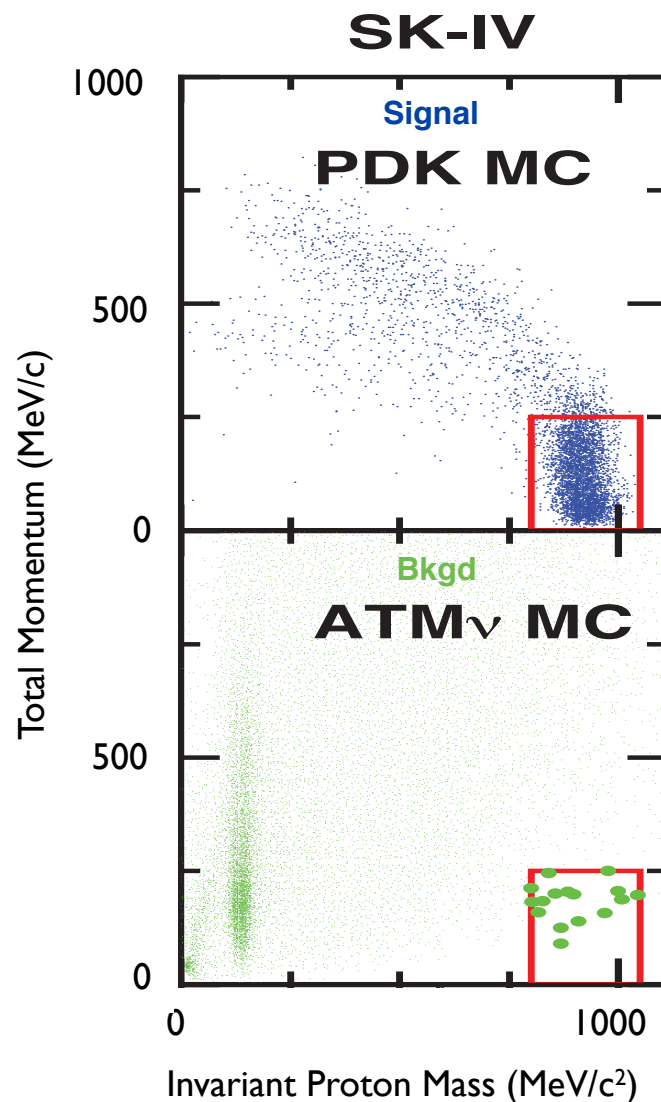

SK-IV

Signal

PDK MC

Total Momentum (MeV/c)

Bkgd

ATMν MC

Invariant Proton Mass (MeV/c²)

The presence of any neutrons can be used to confidently reject PDK backgrounds (with little signal loss)

However the absence of any neutrons is not necessarily a strong indicator of signal (could be detection inefficiency).

Attributing confidence to proton decay candidates without neutrons requires:

· knowledge of the neutron tagging efficiency, and
· **knowledge of how many neutrons are expected per background event**
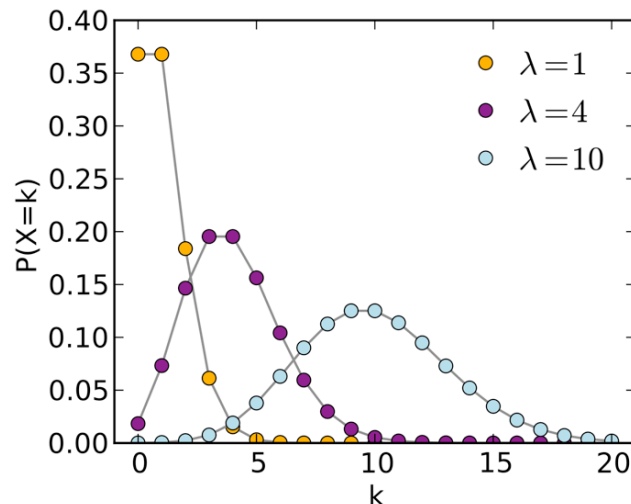
Did we see zero neutrons, given an expectation of 1 or 10? What is the number of expected neutrons? The spread?

It is not enough merely to identify the presence or absence of neutrons

The presence of any neutrons can be used to confidently reject PDK backgrounds (with <10% signal loss)

However the absence of any neutrons is not necessarily a strong indicator of signal. (could be detection inefficiency)

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Some physics analyses require discrimination between different types of neutrino interactions (eg, CC vs NC) with different average neutron abundances.

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- knowledge of the neutron tagging efficiency, and
- **knowledge of how many neutrons are expected per background event**

Some physics analyses require discrimination between different types of neutrino interactions (eg, CC vs NC) with different average neutron abundances.

This requires detailed understanding of the number of final-state neutrons:

The theoretical underpinnings of this observable are not well known
FS neutron abundances have not been well measured
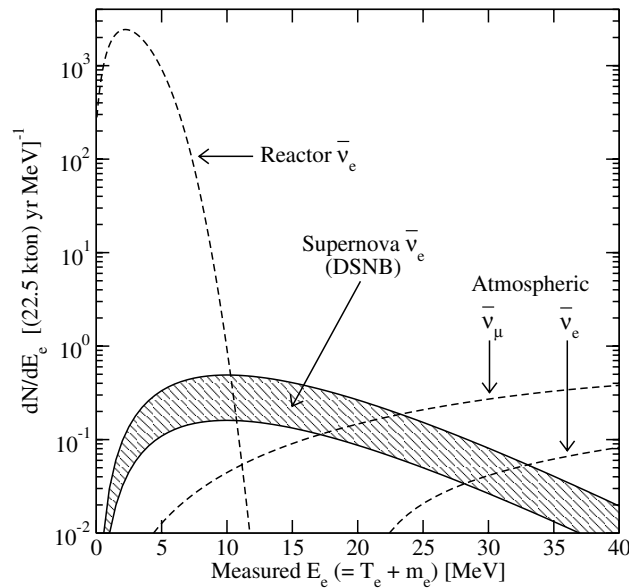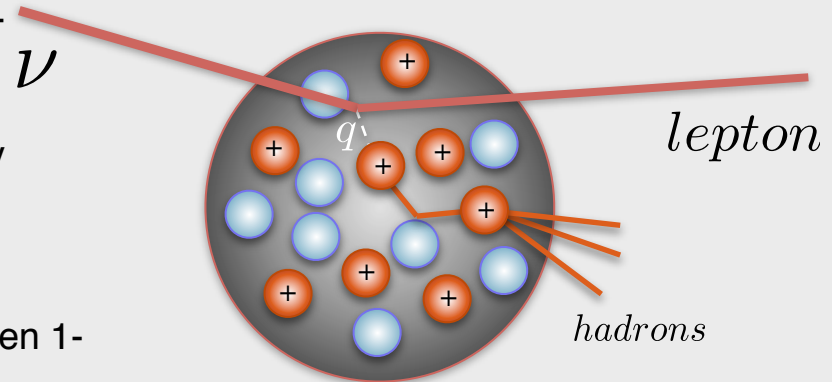
SN neutrino detection

- Neutron tagging can be used to separate between diffuse supernova background (DSNB) neutrinos and various backgrounds.

- In core collapse Supernovae, the technique can be used to statistically discriminate between various flavors and fluxes.
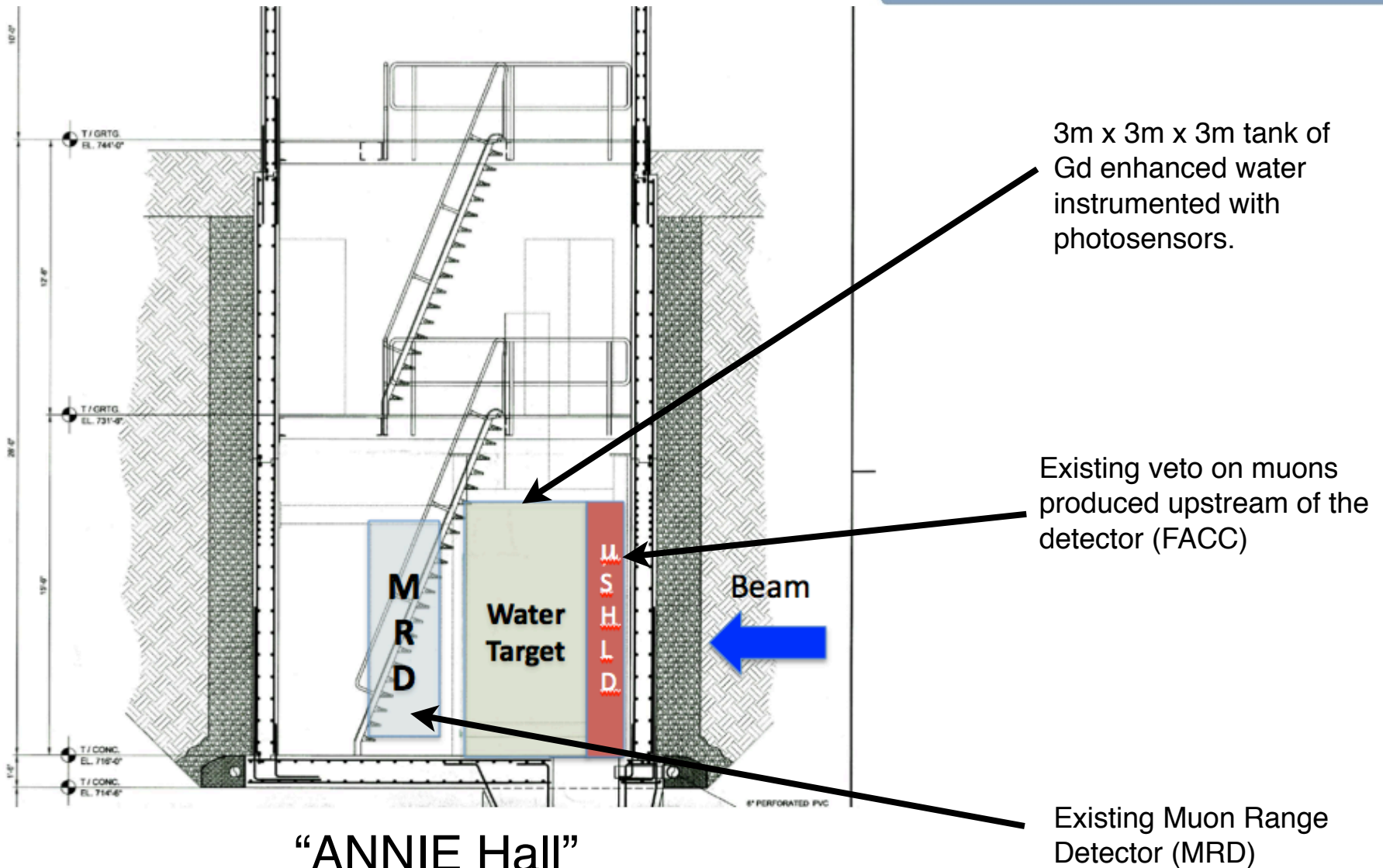
Neutrino interaction Physics

Nuclear models present the largest systematics in water-based oscillation experiments.

Neutron abundances may make it possible to statistically separate between neutral current and charged current interactions.

Neutron multiplicity is also sensitive to differences between 1-body and 2-body currents (where neutrinos scatter off of correlated pairs of nucleons).
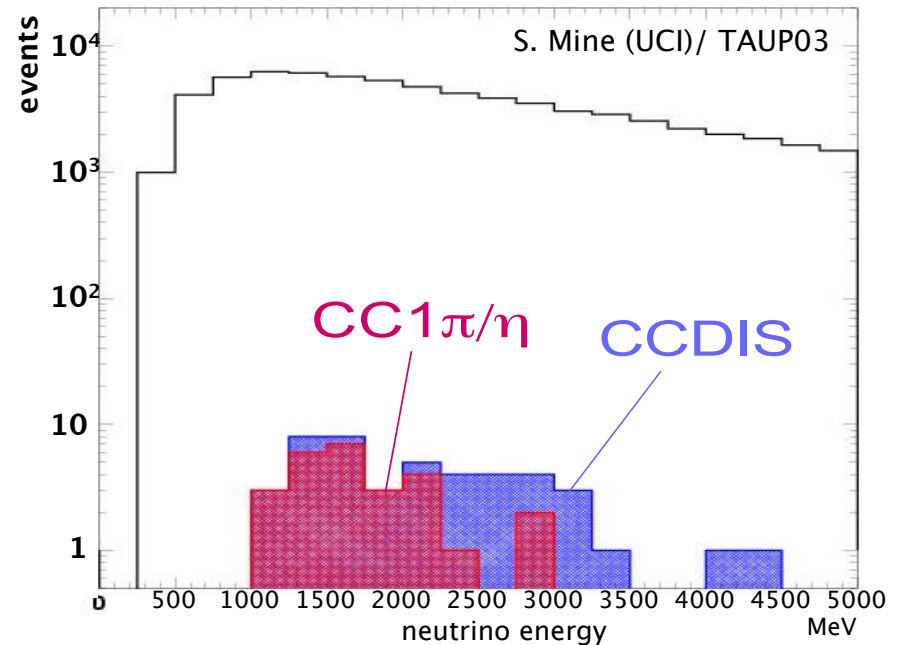
3m x 3m x 3m tank of Gd enhanced water instrumented with photosensors.

Existing veto on muons produced upstream of the detector (FACC)

Existing Muon Range Detector (MRD)

Beam

M R D

Water Target

U S H L D

"ANNIE Hall"

(formerly the SciBooNE pit)

- Expected proton decay backgrounds typically come from interactions between 1-5 GeV.

- The Booster neutrino beam line provides an energy spectrum peaked near 1 GeV.

- We will see several hundreds of v_μ CC interactions per 10^{20} POT per ton in the relevant window, and several tens of events at the highest energies.

proton decay background energies
as measured by Super–K*
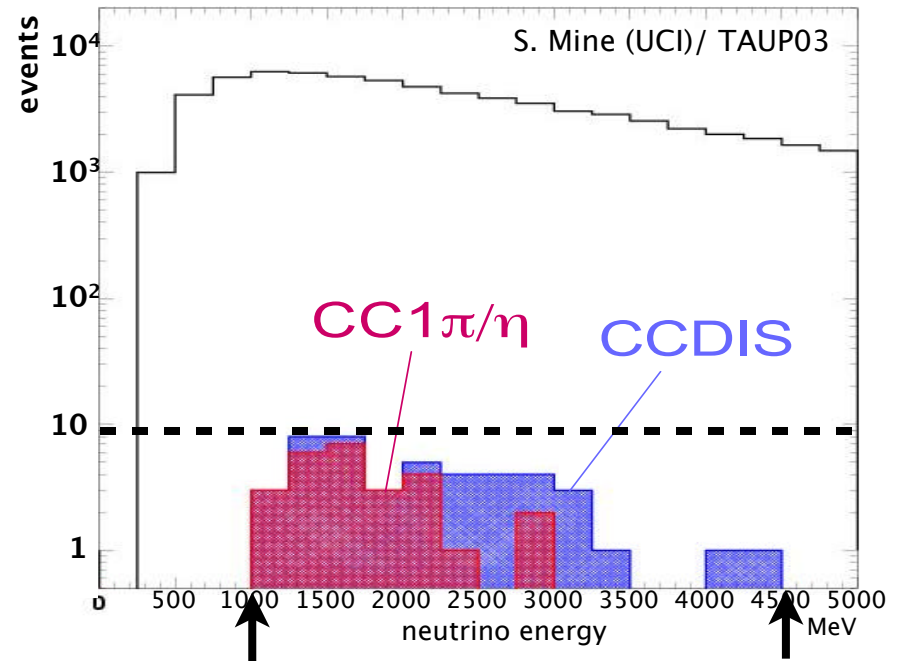
* note: this measurement did not include detection of final–state neutrons.

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S. Mine (UCI)/ TAUP03

CC1π/η CCDIS

neutrino energy

MeV

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Expected Event Rates in Booster Neutrino Beam
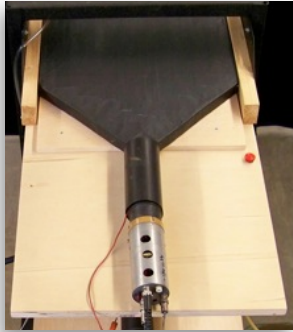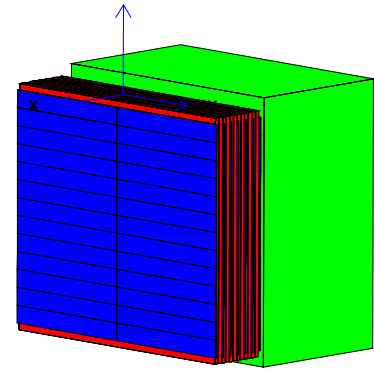Nevts / 10^{20} POT / 200 MeV
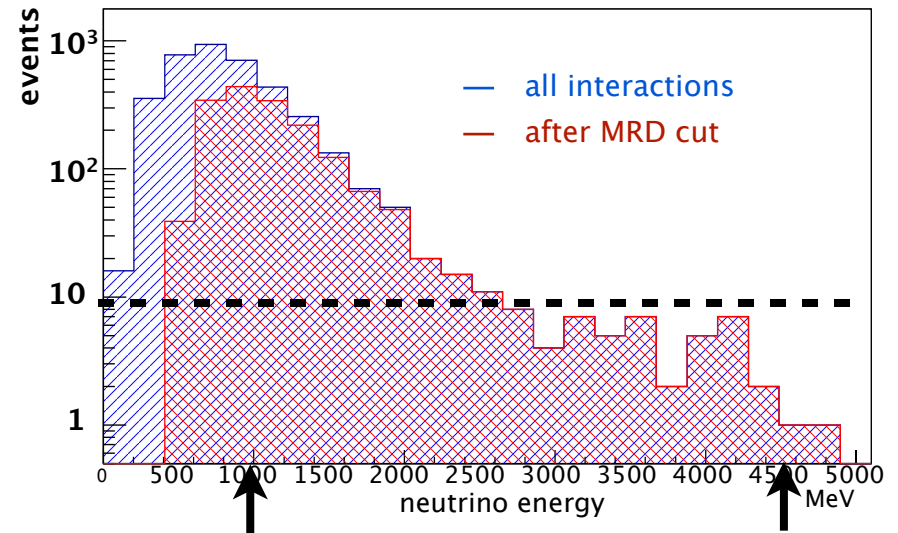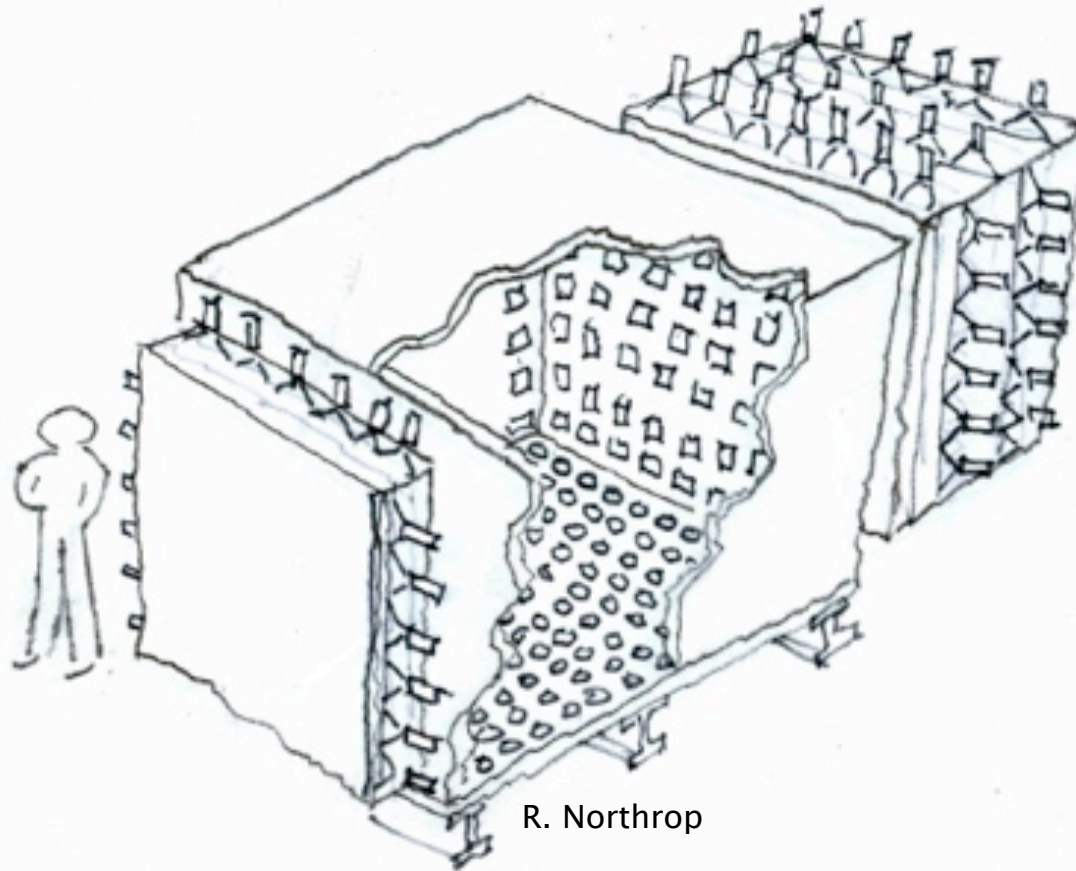
R. Northrop

Front Anti-Coincidence Counter

Muon Range Detector

LAPPDs

Gd-loaded water volume
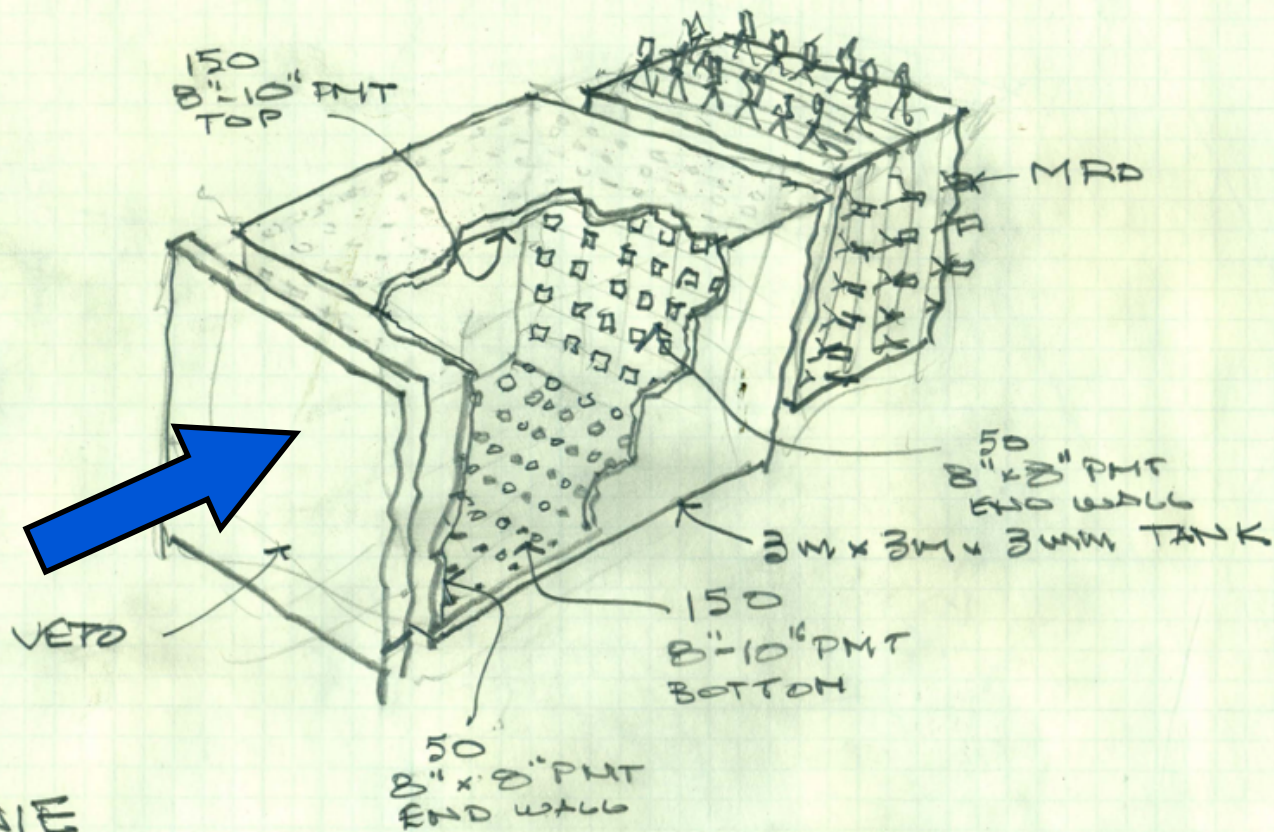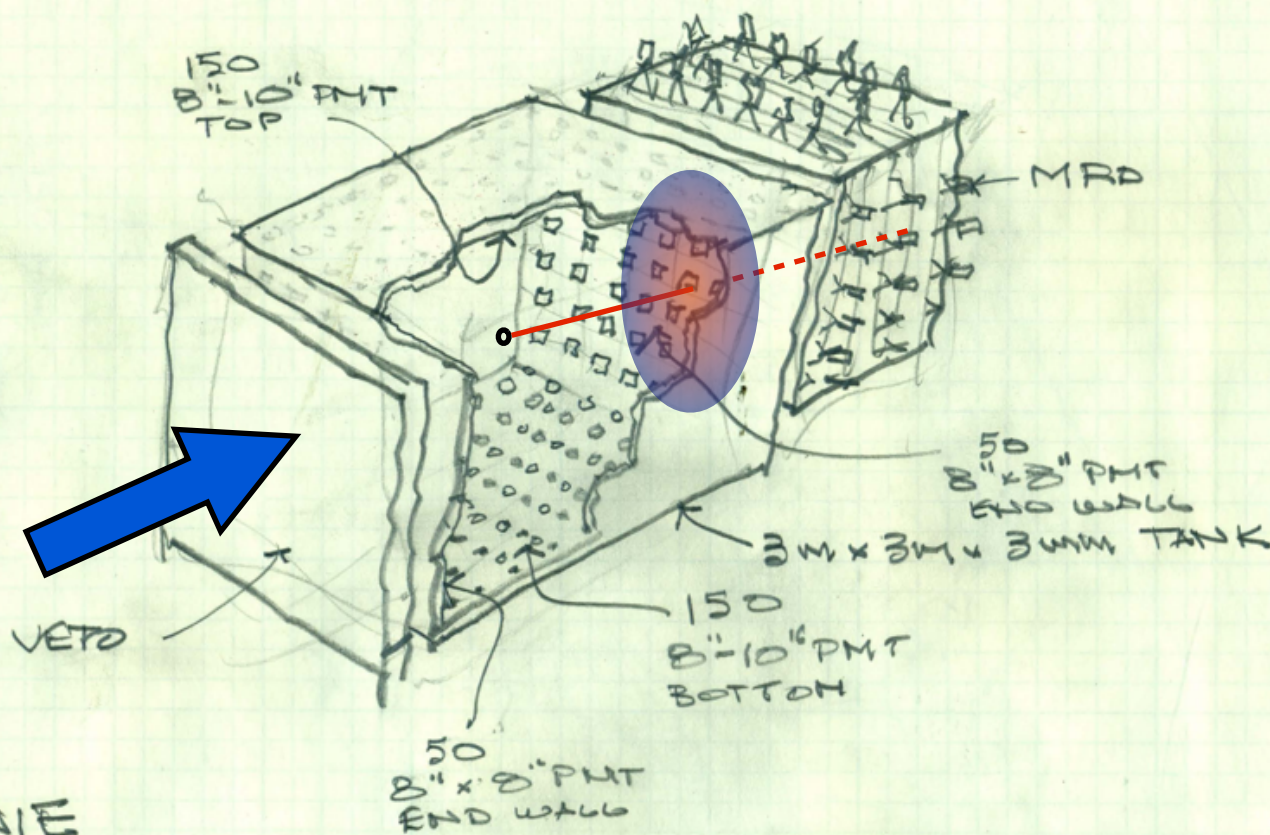
Conventional PMTs

R3600

R. Northrop

R. Northrop

- A muon is produced and detected in the MRD.

- LAPPDs used to reconstruct vertex position based on arrival of Cherenkov light.
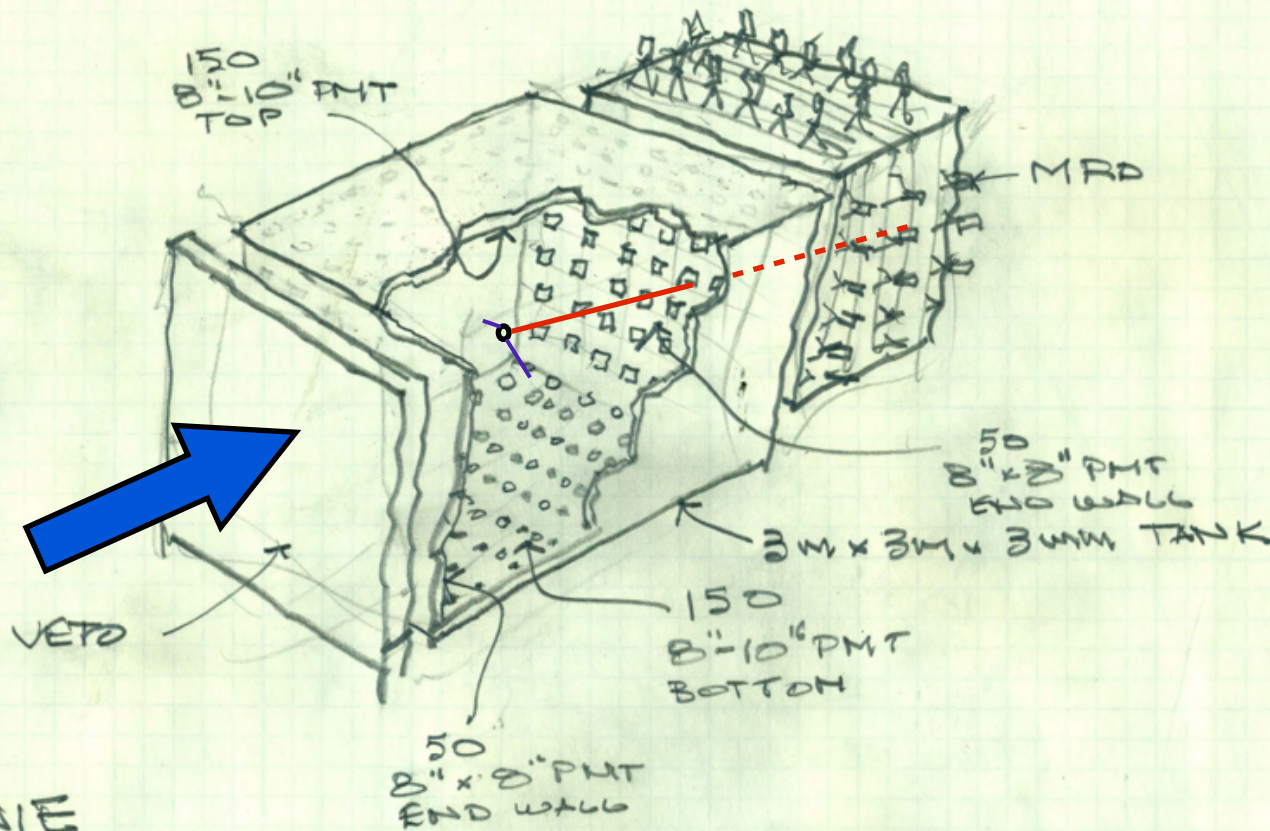
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- Neutrons thermalize

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- Neutrons thermalize and stop.

R. Northrop

- A muon is produced and detected in the MRD.

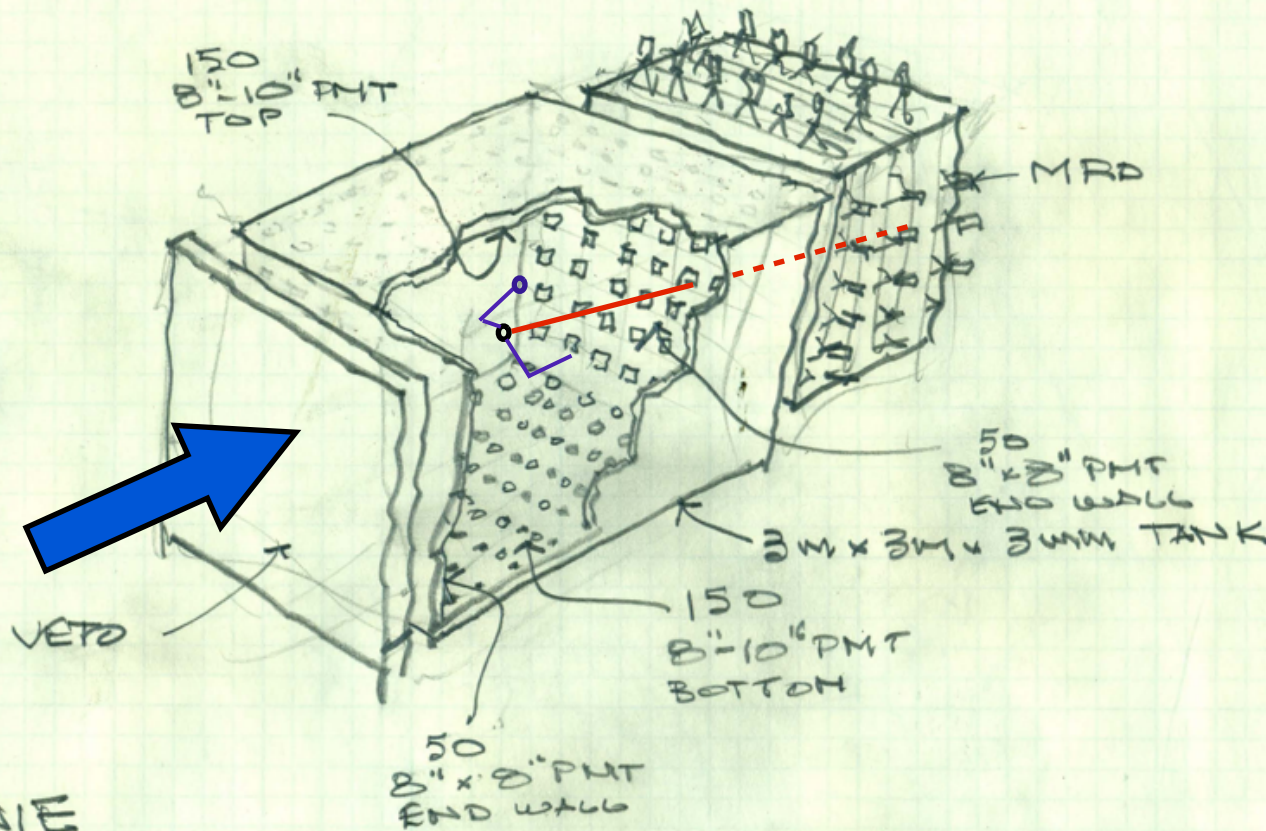- LAPPDs used to reconstruct vertex position based on arrival of Cherenkov light.
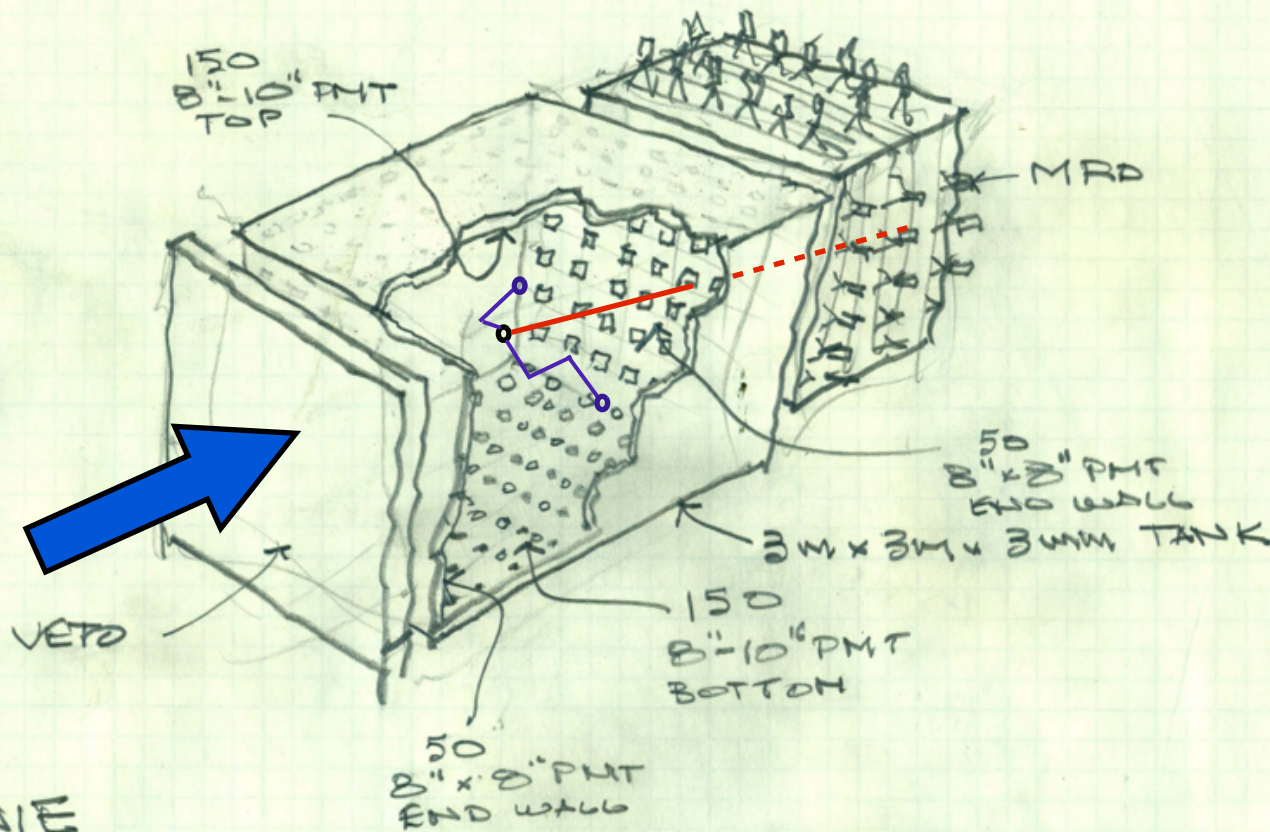
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- Several tens of microseconds later, the neutrons are captured and produce somewhat isotropic flashes of light from typically 3 gamma showers (8 MeV).

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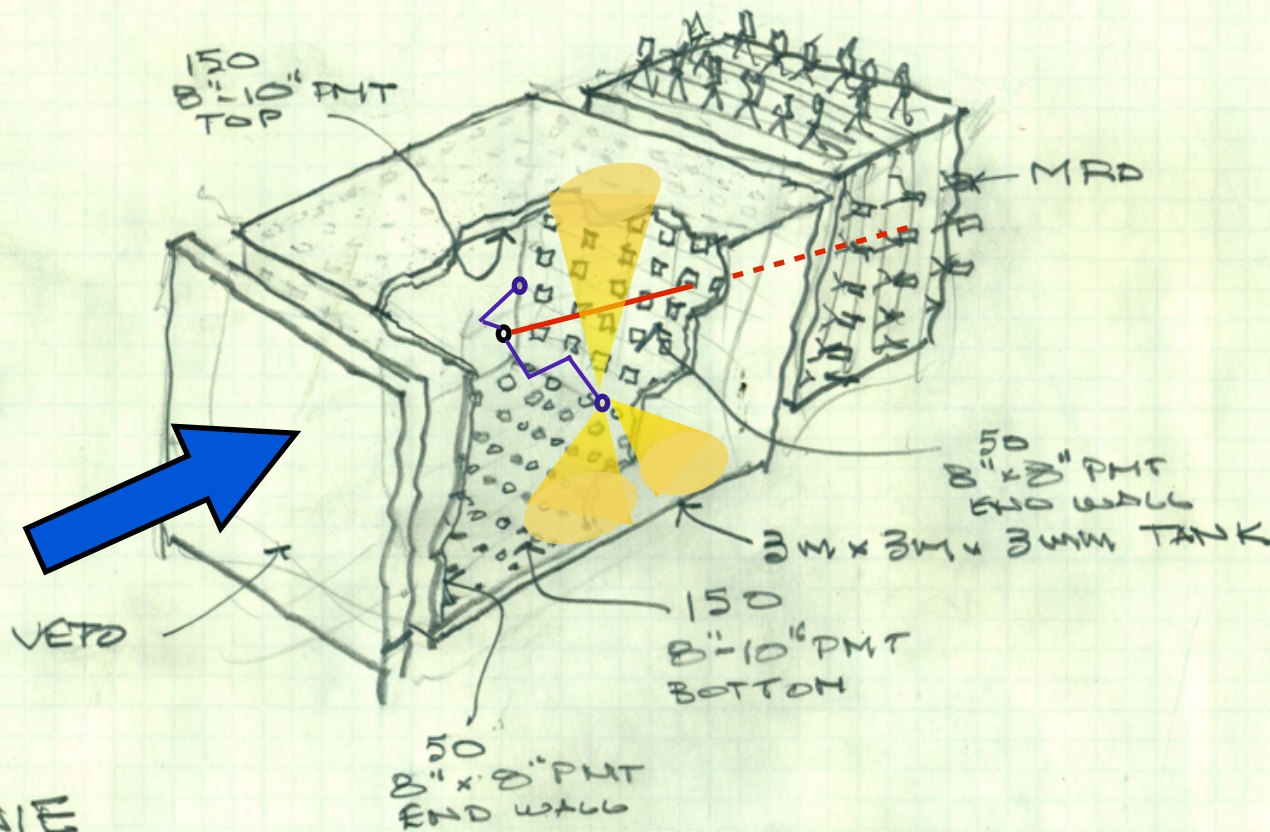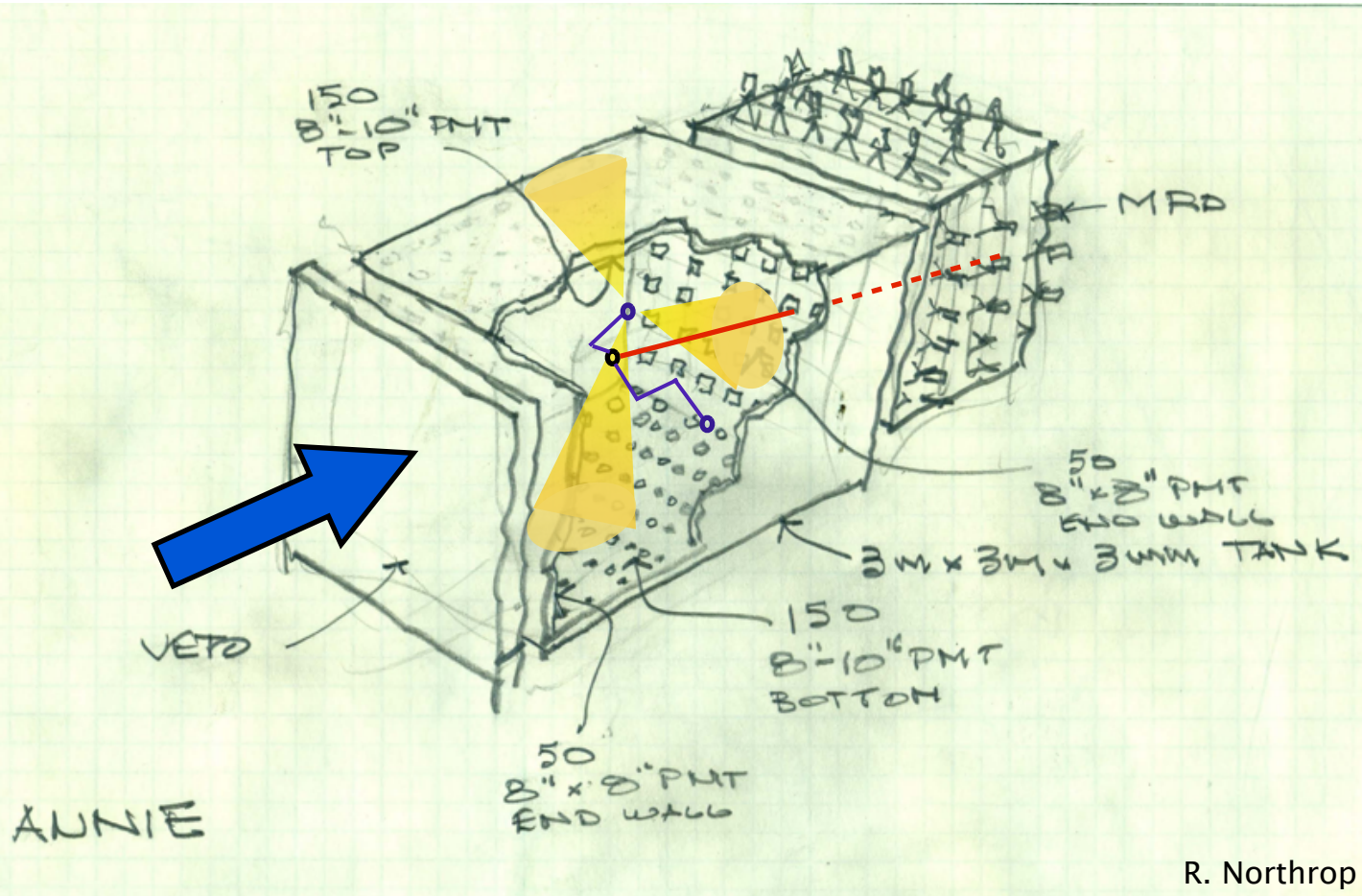
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Neutrons typically drift over a 2 meter distance.

- In the directions transverse to the beam, this 2-meter window is centered symmetrically about the interaction point.
- In the direction of the beam, it is mostly forward with respect to the interaction point.

In order to get a clean sample of neutrons, this analysis must be restricted to a small ~1 ton fiducial volume situated sufficiently far from the walls of the tank to stop the neutrons.

net neutron transit distances (inclusive)

transverse to the beam direction:
— x-direction
— y-direction

parallel the beam:
— z-direction

mm

stopping position of 95% of the neutrons in the transverse directions

stopping position of 95% of the neutrons in the beam direction

In order to identify events in this fiducial volume, we need to reconstruct the interaction vertex to better than 10 cm. Accurate timing based reconstruction from the Cherenkov light is essential.
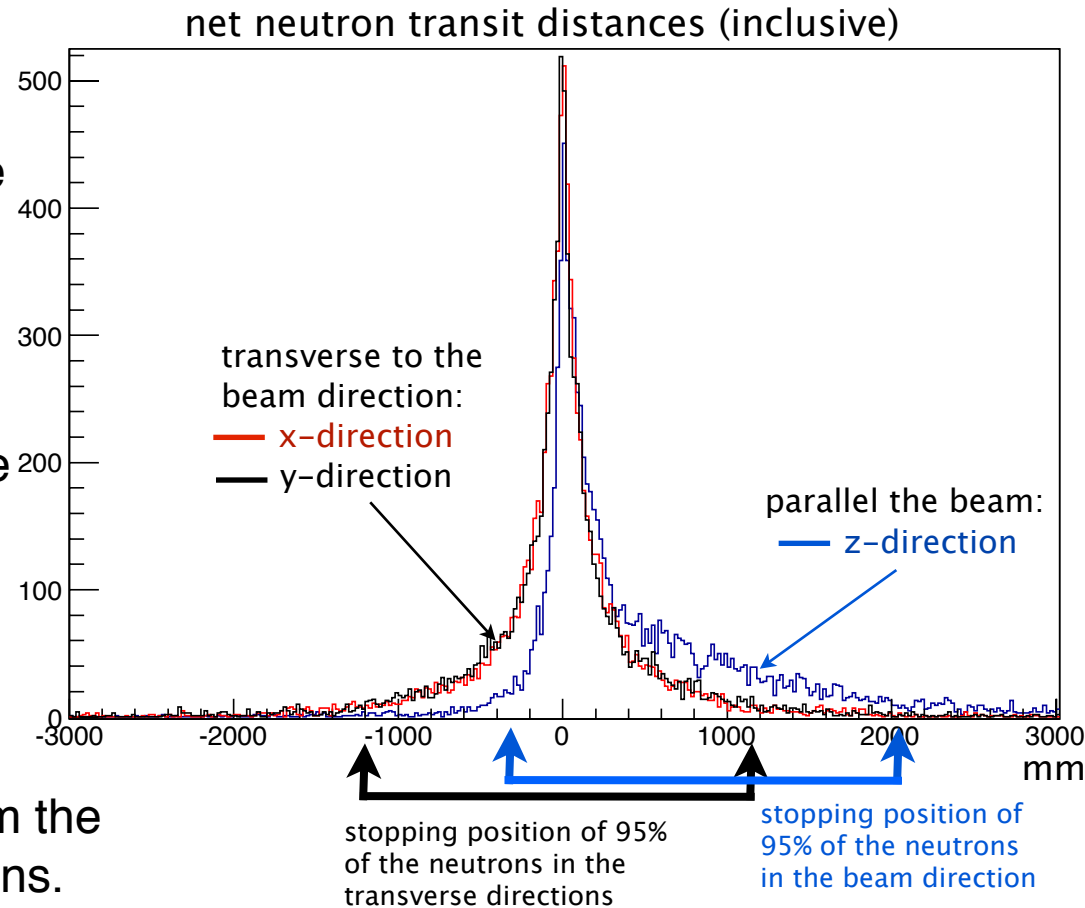
LAPPDs can provide the needed photodetector capabilities

The Large Area Picosecond Photodetectors (LAPPD):

- large, flat-panel, MCP-based photosensors
- <50 psec time resolutions and <1cm spatial resolutions
- based on new, potentially economical industrial processes.
- LAPPD design includes a working readout system.
- Phase II request for $3M for commercialization has been submitted by Incom, Inc

2896 events

~44 psec

26

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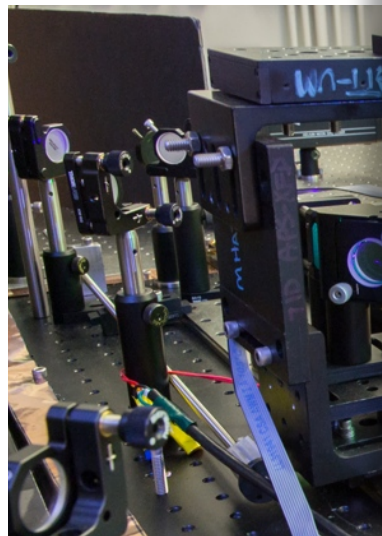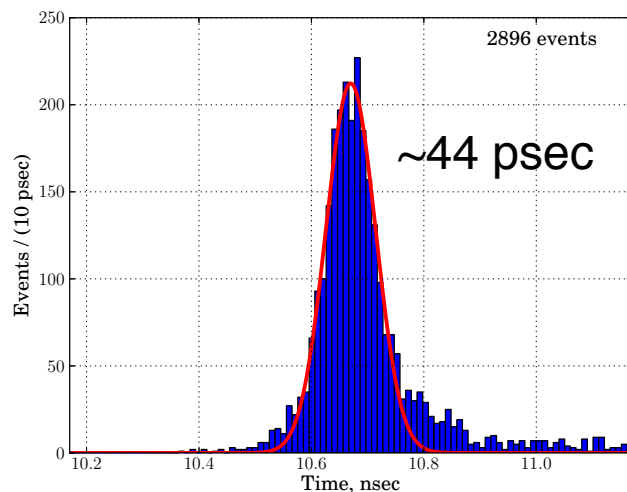- Phase II request for $3M for commercialization has been submitted by Incom, Inc

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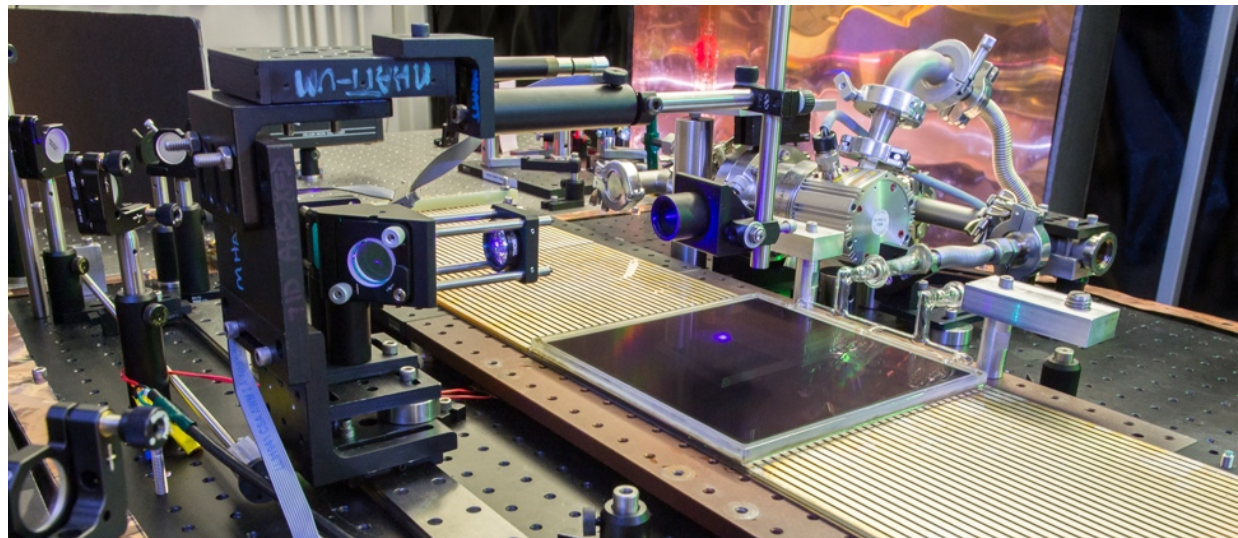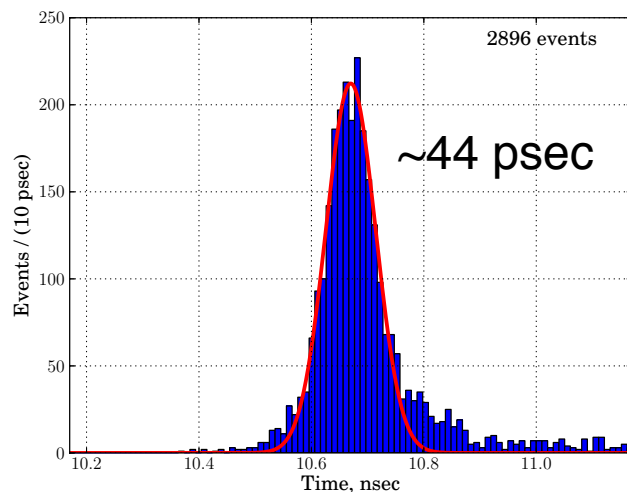
Fermilab PAC Meeting – Jan 22, 2013

a few key LAPPD papers

H. Grabas, R. Obaid, E. Oberla, H. Frisch J.-F. Genat, R. Northrop, F. Tang, D. McGinnis, B. Adams, and M. Wetstein; *RF Strip-line Anodes for Psec Large-area MCP-based Photodetectors*, Nucl. Instr. Meth. A71, pp124-131, May 2013

B. Adams, M. Chollet, A. Elagin A. Vostrikov, M. Wetstein, R. Obaid, and P. Webster; *A Test-facility for Large-Area Microchannel Plate Detector Assemblies using a Pulse Sub-picosecond Laser;* Review of Scientific Instruments 84, 061301 (2013)

E. Oberla, J.-F. Genat, H. Grabas, H. Frisch, K. Nishimura, and G Varner; A 15 GSa/s, 1.5 GHz *Bandwidth Waveform Digitizing ASIC*; Nucl. Instr. Meth. A735, 21 Jan., 2014, 452; http://dx.doi.org/10.1016/j.nima.2013.09.042; arxiv:http://arxiv.org/abs/1309.4397

O.H.W. Siegmund,*, J.B. McPhate, J.V. Vallerga, A.S. Tremsin, H. Frisch, J. Elam, A. Mane, and R. Wagner; *Large Area Event Counting Detectors with High Spatial and Temporal Resolution;* submitted to JINST; Dec, 2013

See http://psec.uchicago.edu for more references

New technologies often require new reconstruction strategies.

Groups at U Chicago, Iowa State, and Argonne have done considerable work on the application of LAPPDs to W Ch detectors.

Preliminary work, specifically for ANNIE shows promise: a very simple starting algorithm gives resolutions close to our target.

85% of events within 10 cm

sigma < 5 cm

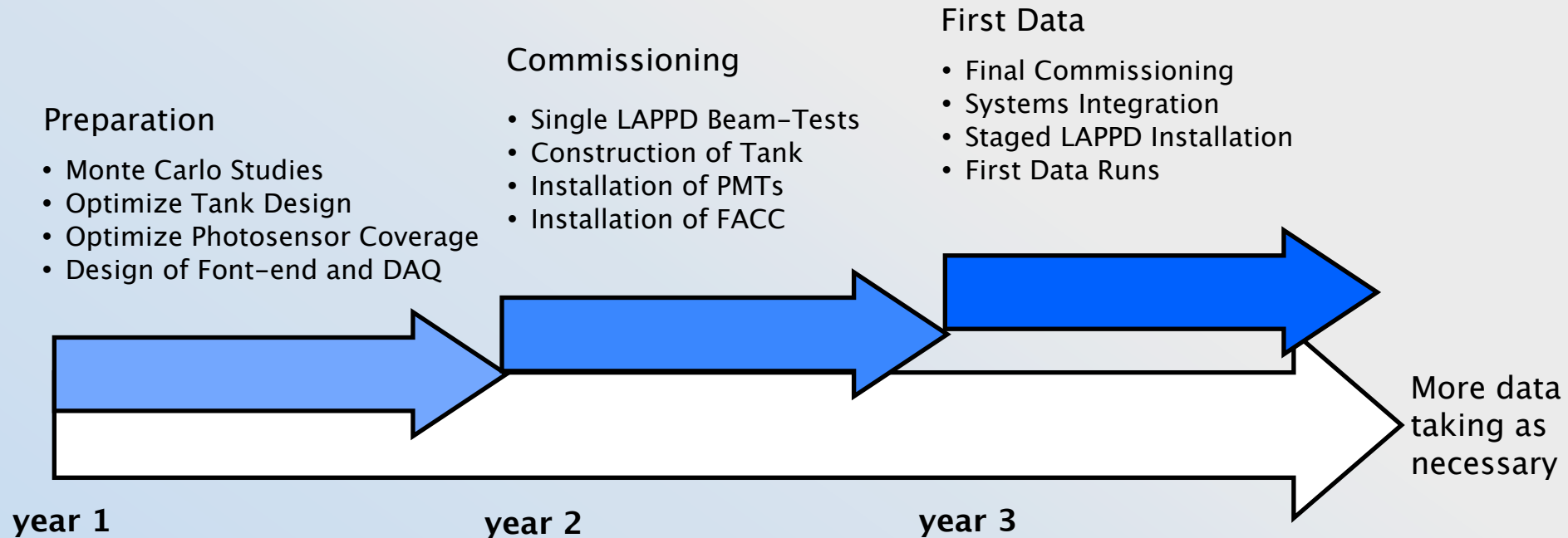(fitted - true vertex) along track direction
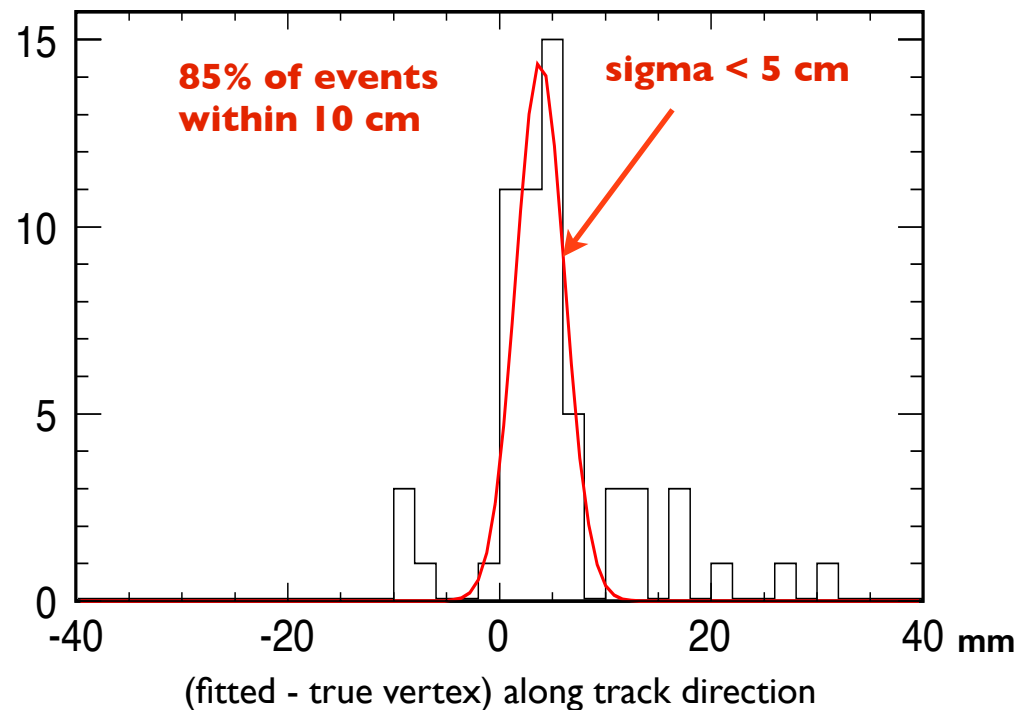
These techniques need to be further developed and optimized for the ANNIE detector. We also need these results to guide optimization of the detector design.
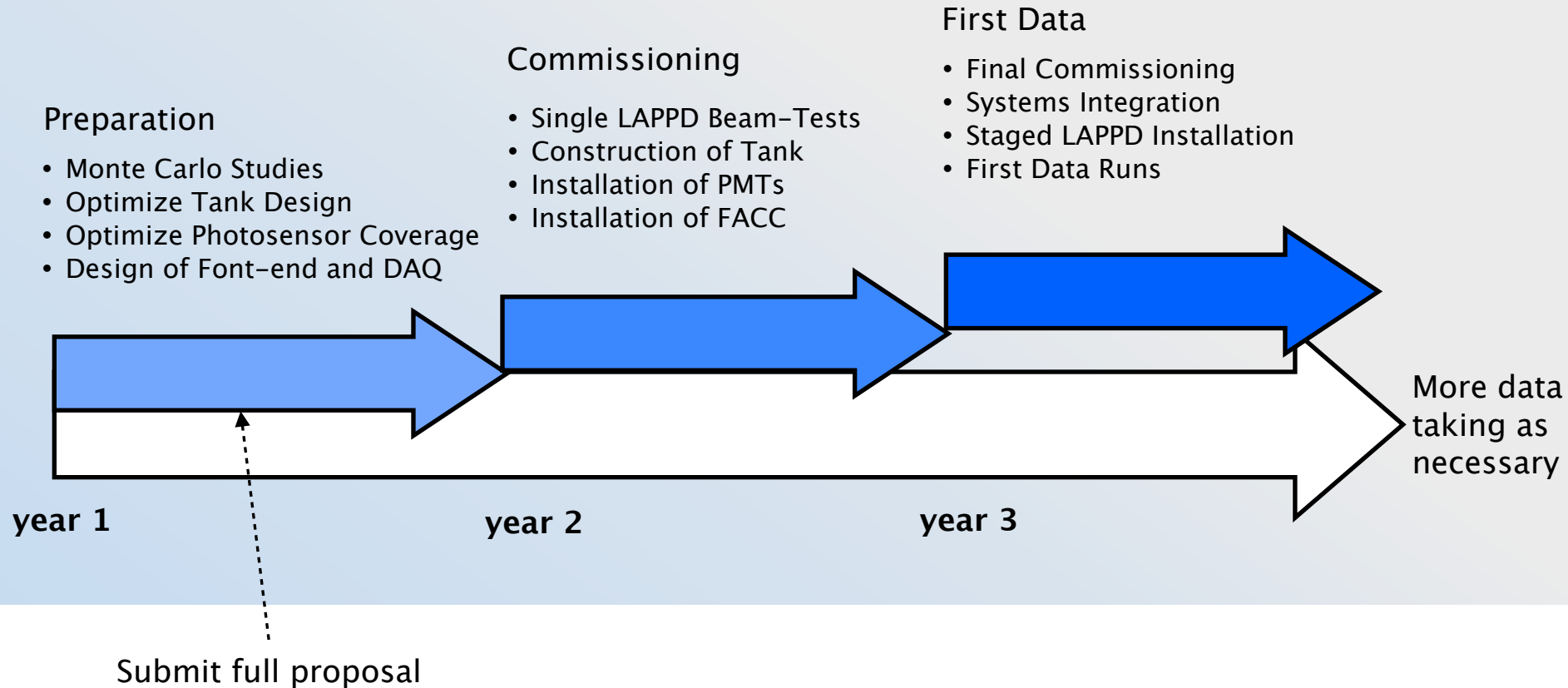
Summary of Tasks/Expertise

- Operation of LAPPDs in a Water Cherenkov detector
  - adapt electronics to the specific needs of ANNIE
  - operational demonstration
  - submersion in water
- Implementation of reconstruction strategy
  - simulations guided design
  - optimization of timing based reconstruction

|	
LAPPDs	ANL, U Chicago
Electronics	U Chicago, U Hawaii
Conventional PMTs	UC Davis, UC Irvine
Water System	UC Davis, UC Irvine
Simulations and Reconstruction	Iowa State, U Chicago, Queen Mary, UC Irvine

Timeline

Preparation

- Monte Carlo Studies
- Optimize Tank Design
- Optimize Photosensor Coverage
- Design of Font-end and DAQ

Commissioning

- Single LAPPD Beam-Tests
- Construction of Tank
- Installation of PMTs
- Installation of FACC

First Data

- Final Commissioning
- Systems Integration
- Staged LAPPD Installation
- First Data Runs

More data taking as necessary

year 1   **year 2**   **year 3**

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More data taking as necessary

year 1

year 2

year 3

Submit full proposal

Preparatory work is already under way and moving quickly

- ANNIE measures an important aspect of neutrino-nuclear interactions with high impact on a variety of physics analyses. This includes a major handle on the limiting backgrounds for proton decay.

- Also represents a working demonstration of new neutrino detection methods, such as a first demonstration of LAPPDs in an optical TPC.

- Capitalizes on largely existing beams and infrastructure and fits in well with the Fermilab Intensity Frontier program.

- The main technical tasks build on a large body of existing work.

- PAC endorsement of the physics mission of ANNIE will solidify effort towards a full proposal for this experiment.

- We request modest support from Fermilab in the form of computing resources, and technical expertise in exploring the best ways to utilize "ANNIE Hall".
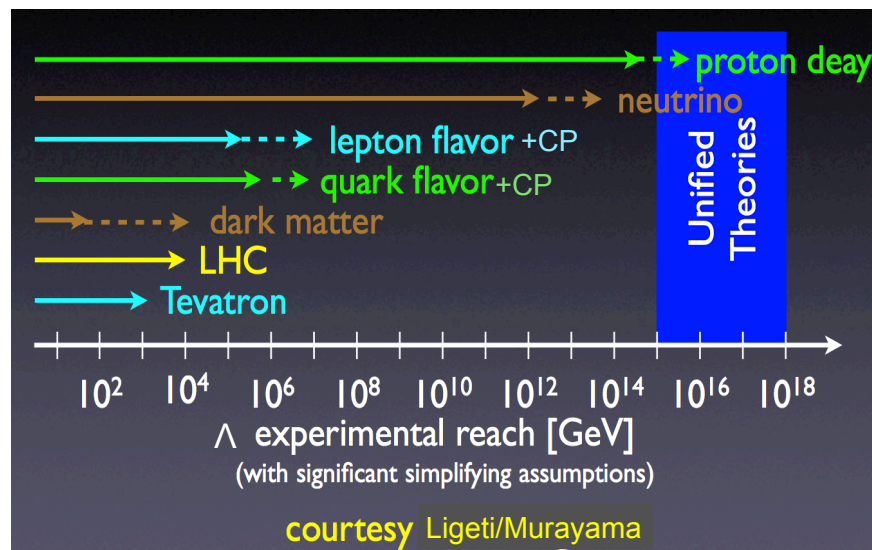
Backup Slides

Especially for the $p \rightarrow e^+ \pi^0$ channel, the most sensitive planned experiments are very large WCh detectors such as Hyperkamiokande.

Nuclear effects are not well understood enough to extrapolate the neutron abundances in water from other target materials.

ANNIE

Atmospheric Neutrino Neutron Interaction Experiment
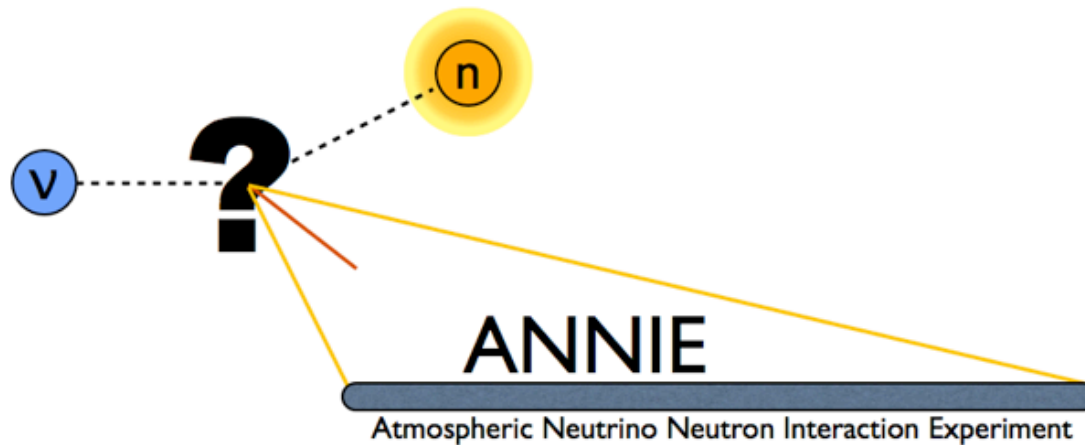
Also, this is not a conventional WCh detector. It is an optical, tracking detector.

Tighter momentum cuts to select only free proton decays do succeed in reducing backgrounds from a few events per Mton per year to 0.15 events per Mton per year (roughly a factor of 10 reduction).

However, they also reduce the efficiency by a factor of 2

Still good, but could use further improvements.

One would still like smaller backgrounds with less inefficiency.

More importantly :

In the case of an observed candidate, one would still like an unambiguous signature. Neutron tagging will greatly help, in this regard.

$e^+\pi^0$ proton decay MC

Total momentum (MeV/c) vs Invariant proton mass (MeV/c^2)

Background event fractions
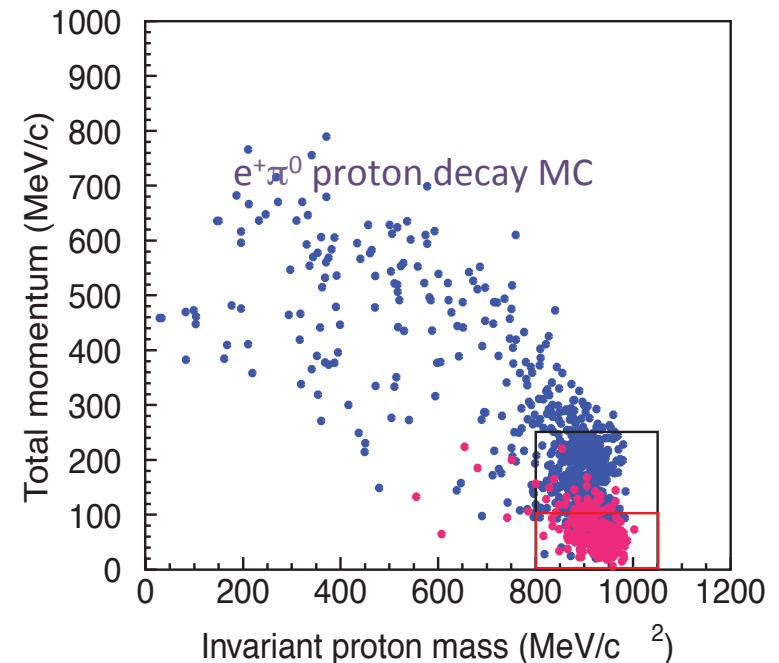
CC no neutrons

- direct interaction of an anti-neutrino on a proton, converting it into a neutron
- secondary (p,n) scattering of struck nucleons within the nucleus
- charge exchange reactions of energetic hadrons in the nucleus (e.g., $\pi^- + p \rightarrow n + \pi^0$)
- de-excitation by neutron emission of the excited daughter nucleus
- capture of π^- events by protons in the water, or by oxygen nuclei, followed by nuclear breakup
- secondary neutron production by proton scattering in water

Neutron production in proton decay events?

- For water, 20% of all protons are essentially free. If these decay, there is no neutron produced as the π^0 would decay before scattering in the water, and 400 MeV electrons rarely make hadronic showers that result in free neutrons.

- Oxygen is a doubly-magic light nucleus, and hence one can use a shell model description with some degree of confidence. Since two protons are therefore in the $p_{1/2}$ valence shell, if they decay to ^{15}N, the resultant nucleus is bound and no neutron emission occurs except by any final state interactions (FSI) inside the nucleus.

- Similarly, if one of the four protons in the $p_{3/2}$ state decays, a proton drops down from the $p_{1/2}$ state emitting a 6 MeV gamma ray, but the nucleus does not break up except by FSI.

- Finally, if one of the two $s_{1/2}$ protons decays, there is a chance that the nucleus will de-excite by emission of a neutron from one of the higher shells.

- 8% x 80% = 6% proton decays with neutrons (Ejiri)

Hole	Residual	States	(k)	E_γ	E_p		E_n	$B(k)$
$(p_{1/2})_p^{-1}$	g.s.	$\frac{1}{2}^-$	^{15}N	0	0		0	0.25
$(p_{3/2})_p^{-1}$	6.32	$\frac{3}{2}^-$	^{15}N	6.32	0	*some*	0	0.41
	9.93	$\frac{3}{2}^-$	^{15}N	9.93	0	*gammas*	0	0.03
	10.70	$\frac{3}{2}^-$	^{15}N	0	0.5		0	0.03
$(s_{1/2})_p^{-1}$	g.s.	1^+	^{14}N	0	0		~20	0.02
	7.03	2^+	^{14}N	7.03	0		~13	0.02
	g.s.	$\frac{1}{2}^-$	^{13}C	0	1.6		~11	0.01
	g.s.	0^+	^{14}C	0	~21		0	0.02
	7.01	2^+	^{14}C	7.01	~14		0	0.02
	g.s.	$\frac{1}{2}^-$	^{13}C	0	~11		~2	0.03
$(j)_p^{-1}$	others		many states	$\leq 3-4$				0.16

few neutrons

H. Ejiri Phys. Rev. C48 (1993)

Hole	Residual
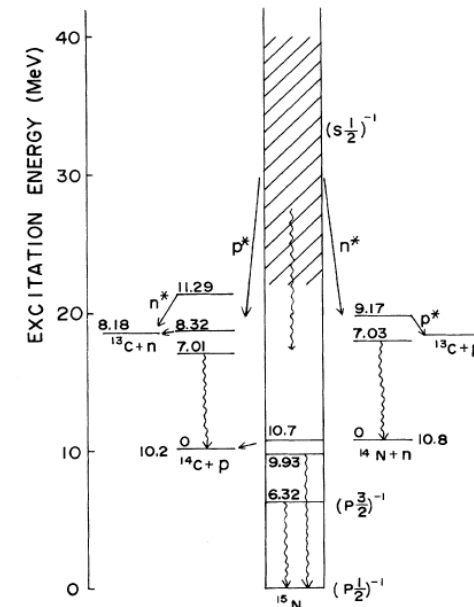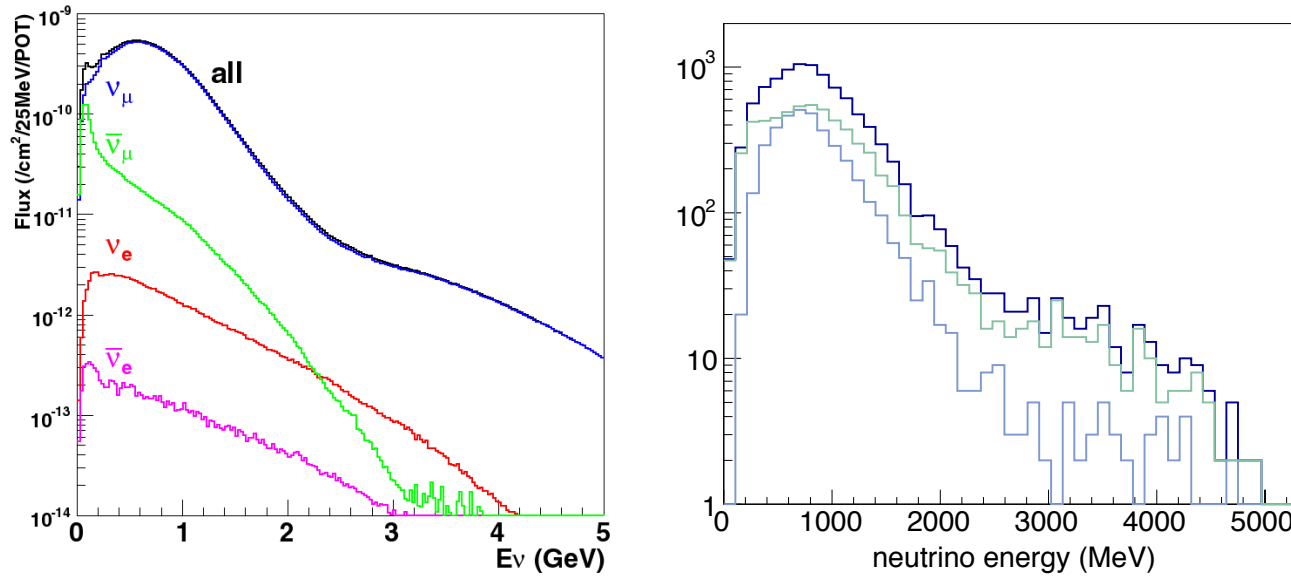
ν-type	Total Interactions	Charged Current	Neutral Current
ν_μ	10210	7265	2945
$\bar{\nu}_\mu$	133	88	45
ν_e	70	52	20
$\bar{\nu}_e$	4.4	3	1.4

Table 1: Rates expected in 1 ton of water with 1×10^{20} POT exposure at ANNIE Hall.

events w/ neutron tag   events w/ NO neutron tag
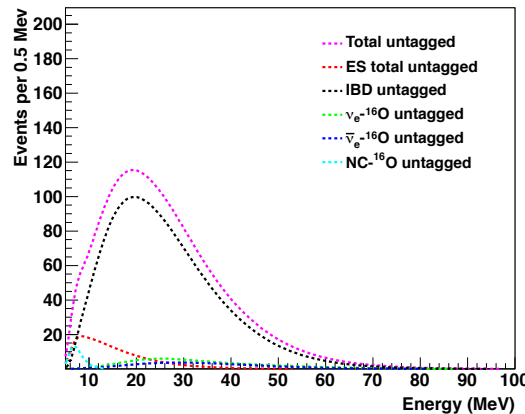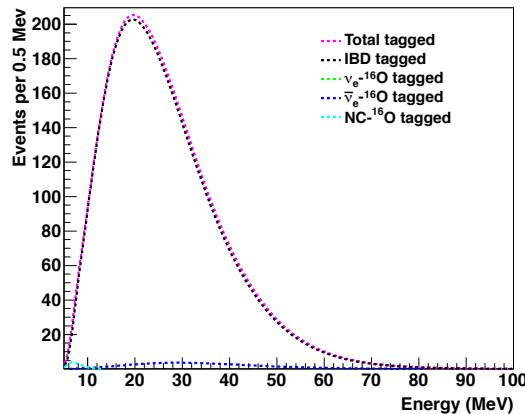
FIG. 46. Total events in WC showing contribution from the different interaction channels, for neutron-tagged (left) and untagged (right) events.

- SN burst interactions with a neutron provide a very pure IBD sample

- Interactions without an FS neutron provide a more pure sample of non–IBD interactions.
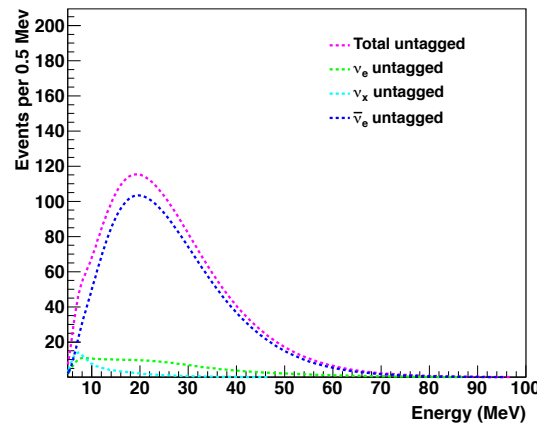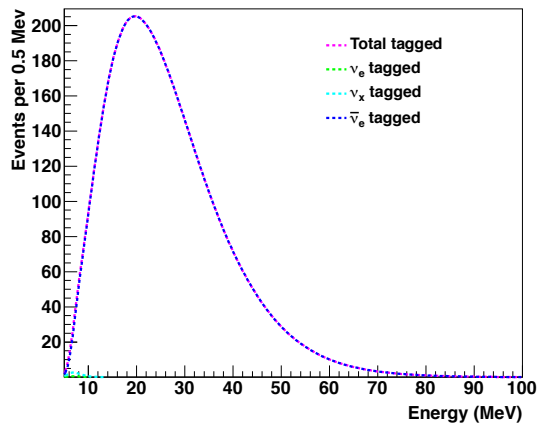
FIG. 47. Total events in WC showing contribution from the different flavors, for neutron-tagged (left) and untagged (right).

- Interactions with neutrons provide a very pure sample of $\overline{\nu}_e$

- Interactions without an FS neutron provide a more pure sample of ν_e, ν_x, $\overline{\nu}_x$
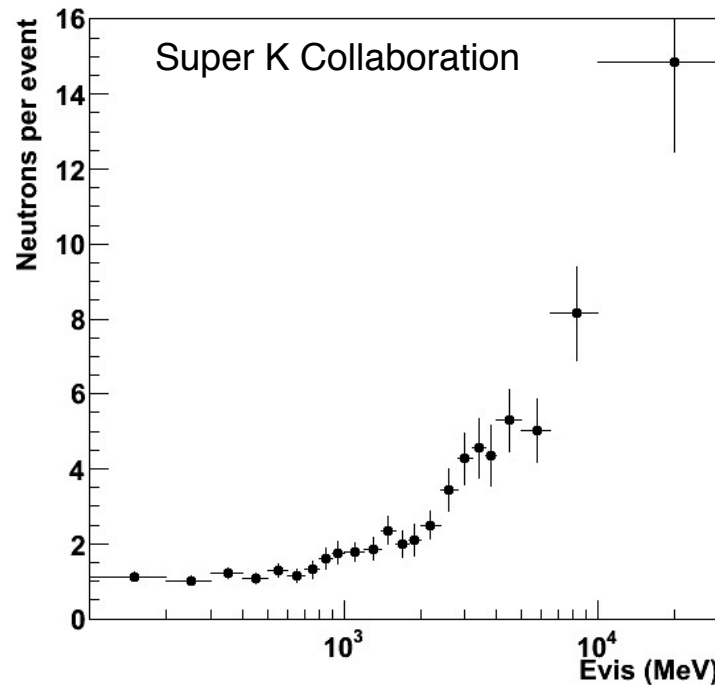
Yes, but not to an extent that they felt publishable:

- inefficient neutron capture on pure water (no Gd)
- uncertainties in flux
- difficulty reconstructing the energy

Nonetheless, this result is promising and strongly motivates a dedicated measurement.
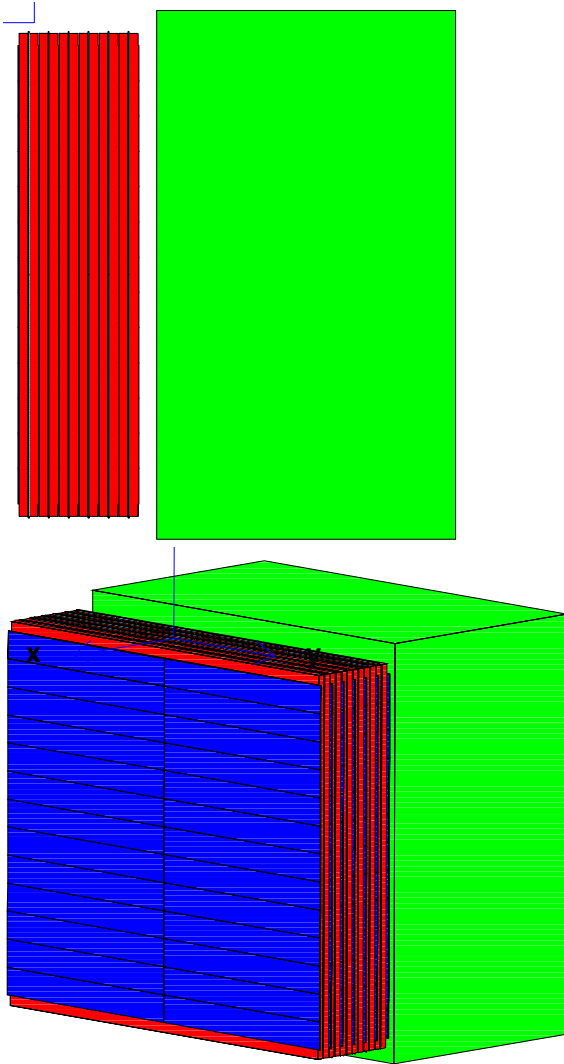
- 12 planes of 2 inch iron plates, and 13 planes of scintillator strips

- vertical scintillator strips are 0.6x138x20, with 13 strips in two sections, for a total of 182 vertical strips in 7 planes

- horizontal strips are 0.6x155x20, with 15 strips in two sections, for a total of 180 vertical strips in 6 planes

Will LAPPDs Be Ready?

- Phase II request for $3M for commercialization has been submitted by Incom, Inc
- We'll have much more clarity on this question in time for the LOI/proposal.
- Incom has been involved in the LAPPD collaboration from the beginning (they make the channel plate substrates) and are very serious.

Price and availability?

- Without a large market or economy of scale, we do not expect the first LAPPDs to be sold at what we hope the asymptotic price will be.
- Nonetheless, we expect them to be significantly cheaper per-unit-area than commercial MCPs
- We also hope, as early adopters, that Incom will be able to negotiate a fair price in order to get their product out to the community
- Members of the ANNIE collaboration have been involved with LAPPD since the beginning. Incom is enthusiastic about ANNIE (see "Letter of Support" from Michael Minot).

Adapting LAPPDs for Water Cherenkov Detectors

Subtasks:

- Further adapt readout system to our experimental needs (precision, buffer depth, acquisition rates). ANNIE events cover two very different time-scales: tens of picoseconds and 10 of microseconds.
- Work out techniques for hi-potting in water
- Operational testing on a small scale

~44 psec
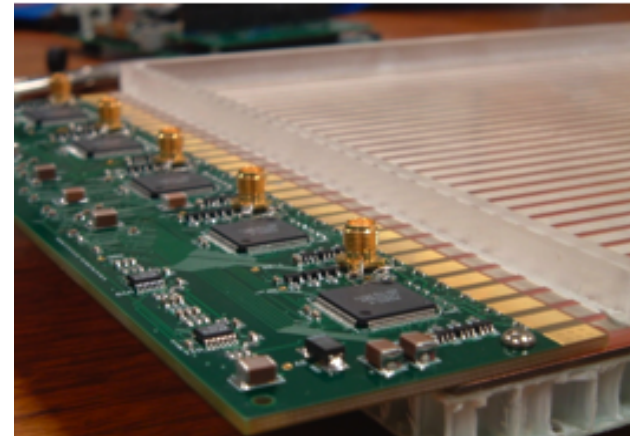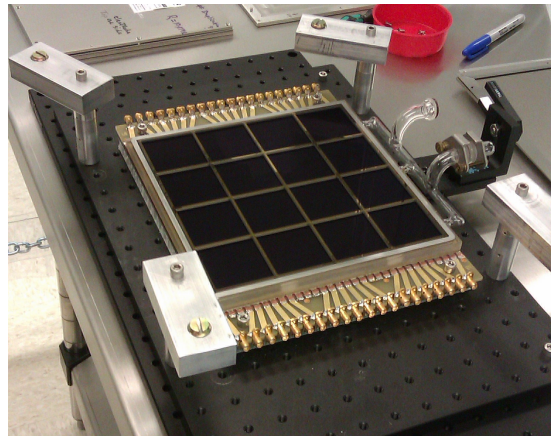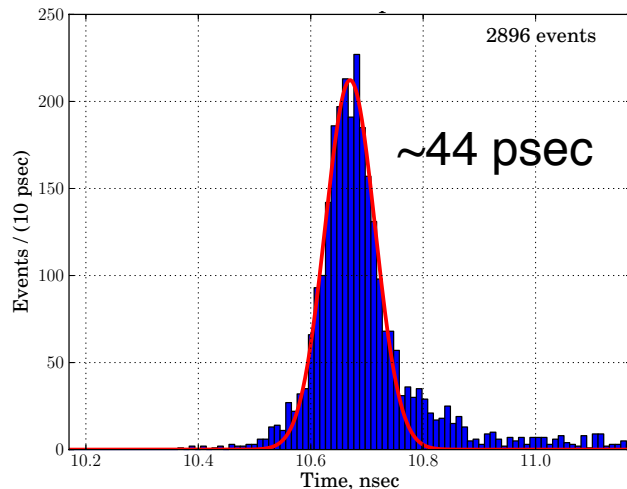
2896 events
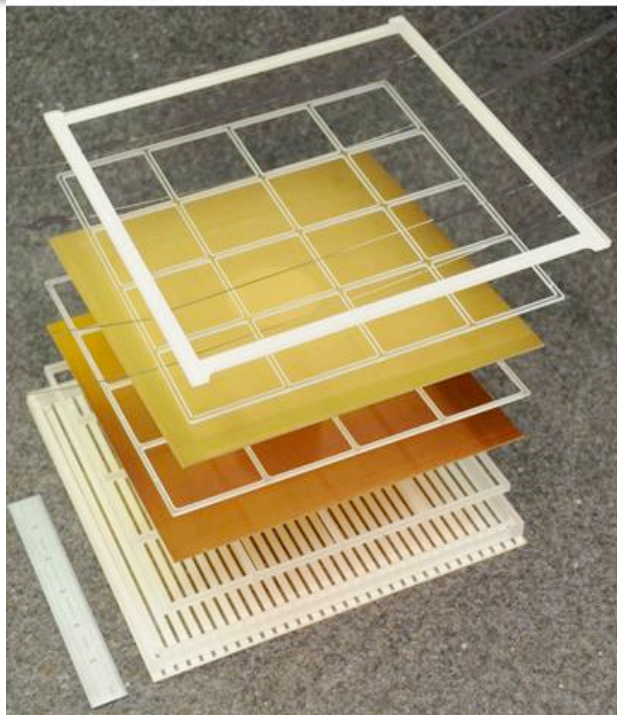
LAPPD detectors:
- Thin-films on borosilicate glass
- Glass vacuum assembly
- Simple, pure materials
- Scalable electronics
- Designed to cover large areas

Conventional MCPs:
- Conditioning of leaded glass (MCPs)
- Ceramic body
- Not designed for large area applications
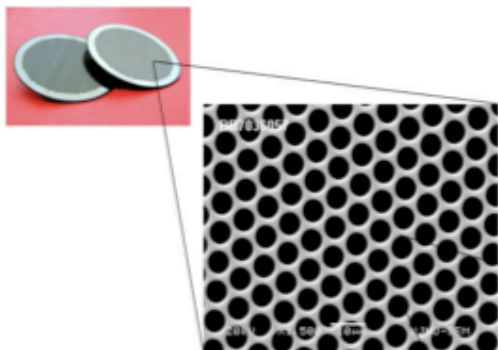
Microchannel Plate (MCP):

- a thin plate with microscopic (typically <50 μm) pores
- pores are optimized for secondary electron emission (SEE).
- Accelerating electrons accelerating across an electric potential strike the pore walls, initiating an avalanche of secondary electrons.

- An MCP-PMT is, sealed vacuum tube photodetector.
- Incoming light, incident on a photocathode can produce electrons by the photoelectric effect.
- Microchannel plates provide a gain stage, amplifying the electrical signal by a factor typically above 10^6.
- Signal is collected on the anode

J. Elam, A. Mane, Q. Peng (ANL-ESD),
N. Sullivan (Arradiance), A. Tremsin (Arradiance, SSL)
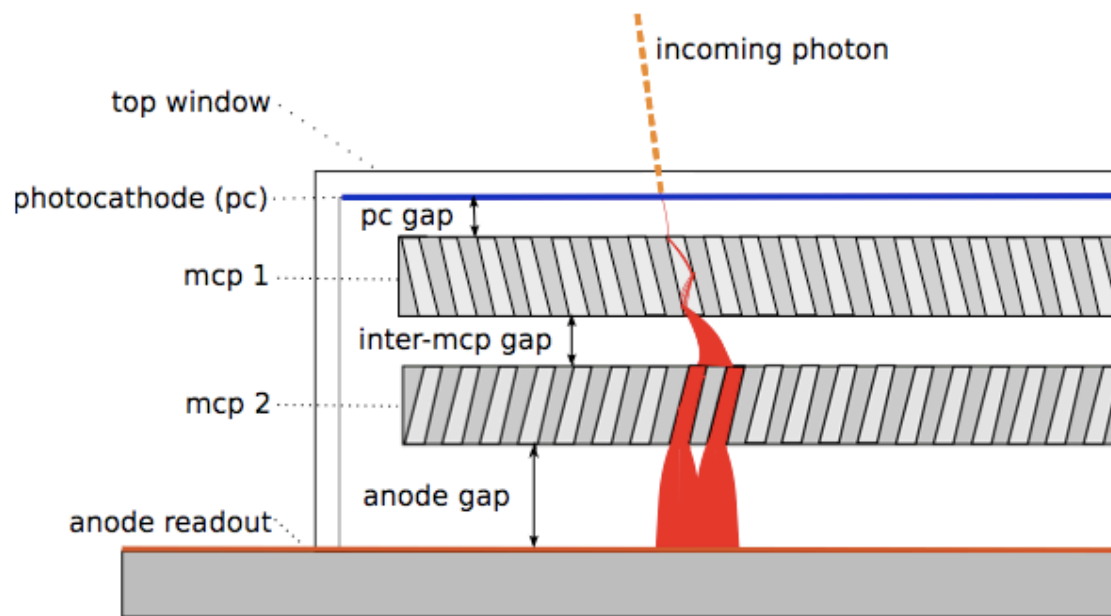
pore

Conventional MCP Fabrication

- Pore structure formed by drawing and slicing lead-glass fiber bundles. The glass also serves as the resistive material

- Chemical etching and heating in hydrogen to improve secondary emissive properties.

- Expensive, requires long conditioning, and uses the same material for resistive and secondary emissive properties. (Problems with thermal run-away).
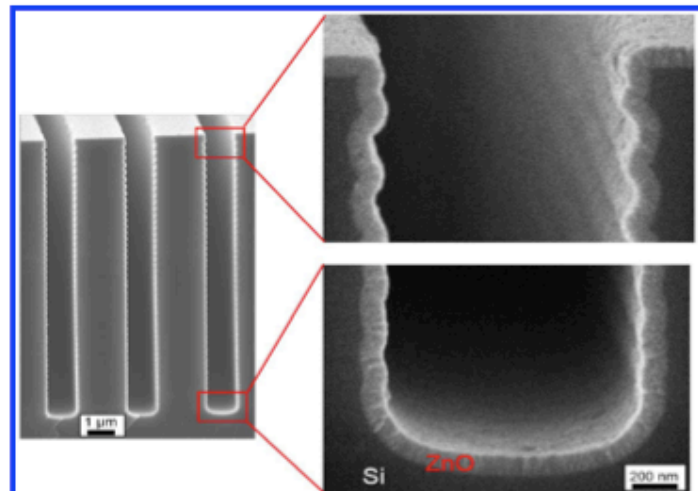
1. porous glass substrate
2. resistive coating (ALD)
3. emissive coating (ALD)
4. conductive coating (thermal evaporation or sputtering)
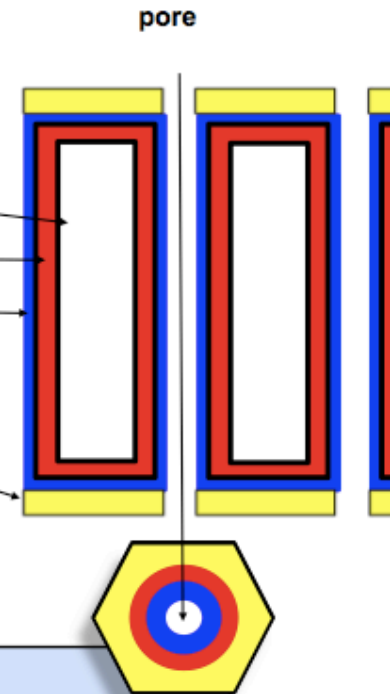
LAPPD Approach

- Separate out the three functions
- Hand-pick materials to optimize performance.
- Use Atomic Layer Deposition (ALD): a cheap industrial batch method.
  - ALD is diffusive, conformal and allows application of material in single atomic monolayers

Channel count (costs) scale with length, not area
Position is determined:

  • by charge centroid in the direction perpendicular to the striplines
  • by differential transit time in the direction parallel to the strips
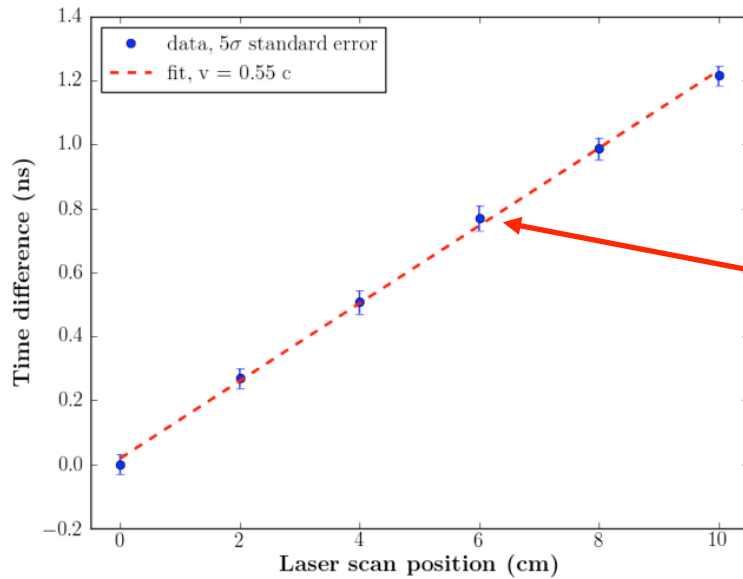
Slope corresponds to ~2/3 c propagations speed on the microstrip lines. RMS of 18 psec on the differential resolution between the two ends: equivalent to roughly 3 mm
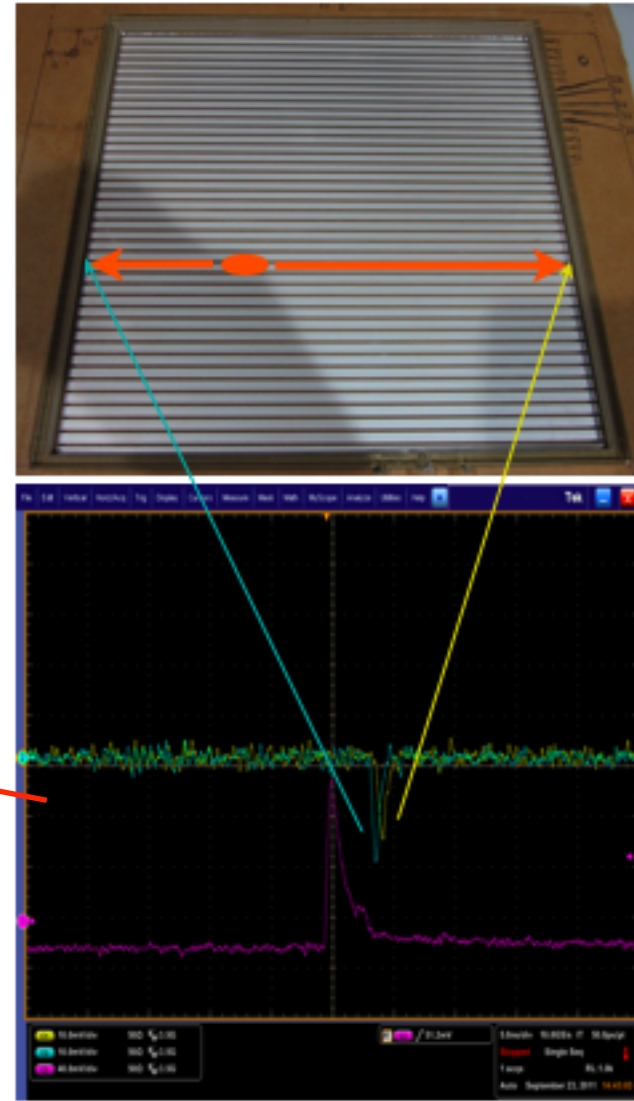
Transverse position is determined by centroid of integrated signal on a cluster of striplines.

Pulses on 10 striplines
Left Side
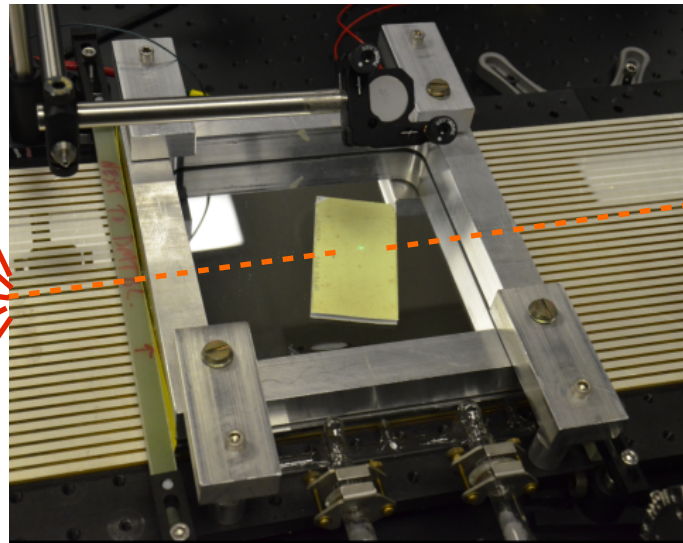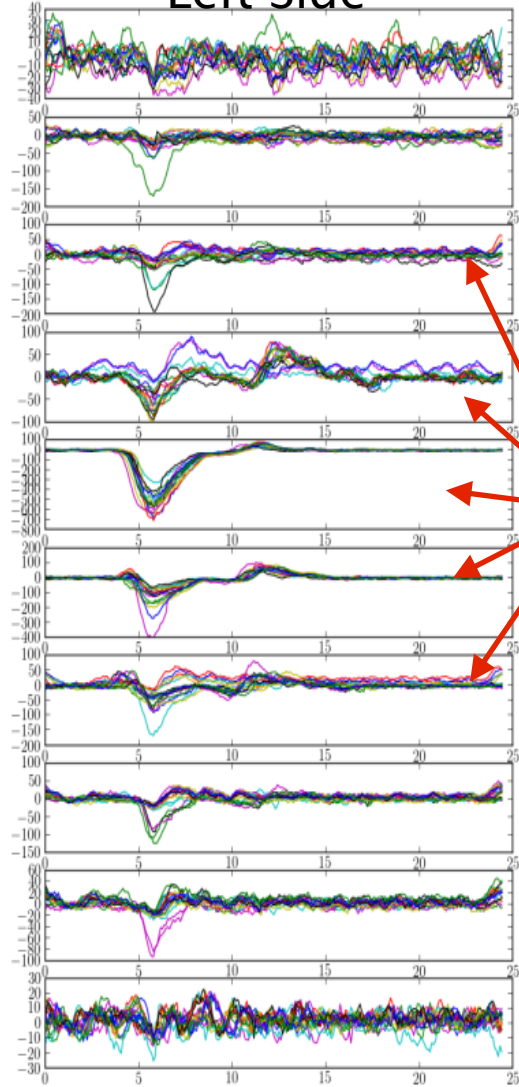
Credit: Eric Oberla
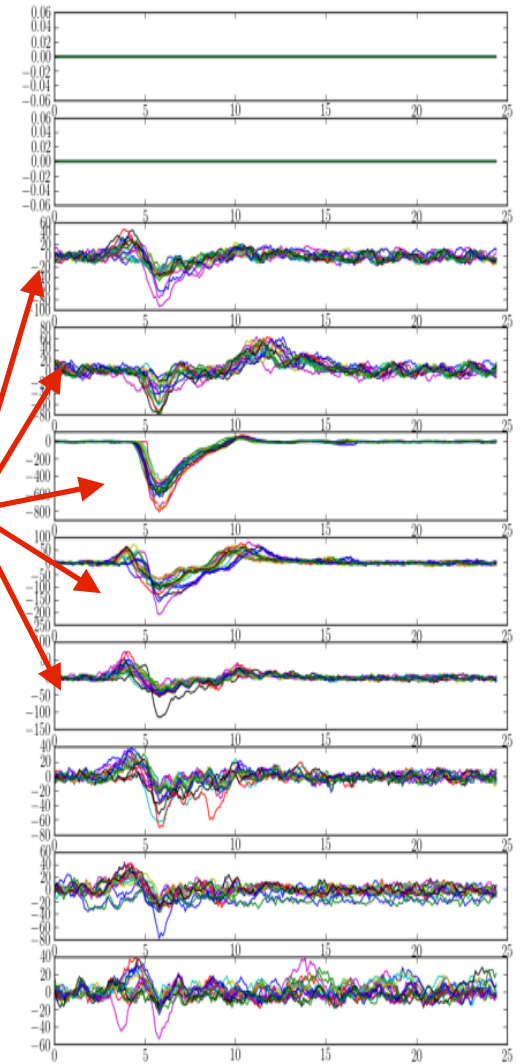
Right Side
Pulses on 10 striplines

Transverse position is determined by centroid of integrated signal on a cluster of striplines.

Pulse Heights (ADC counts)
Left Side
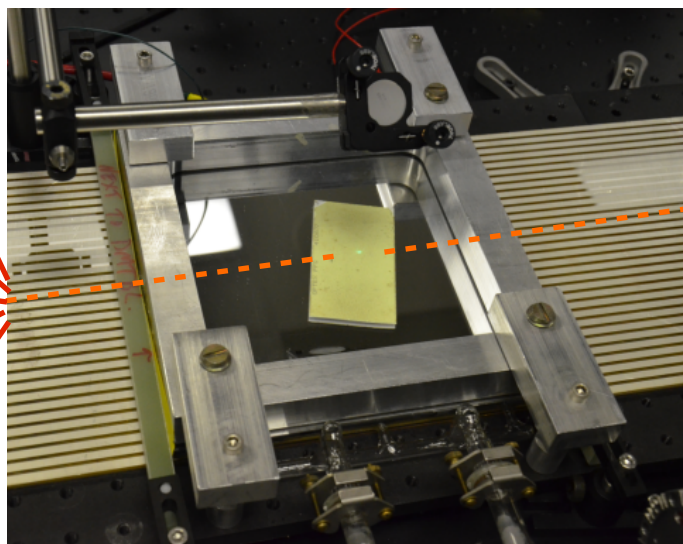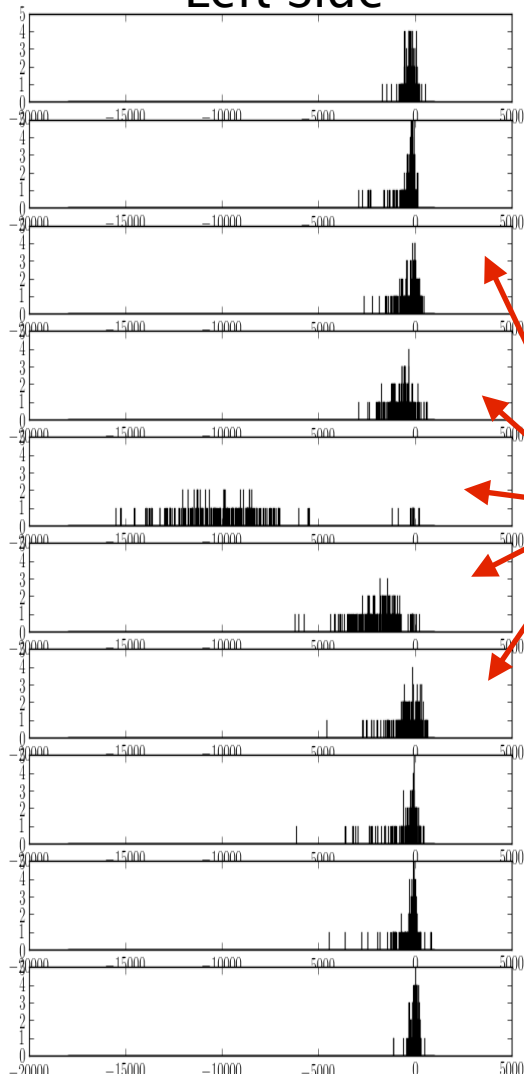
Credit: Eric Oberla
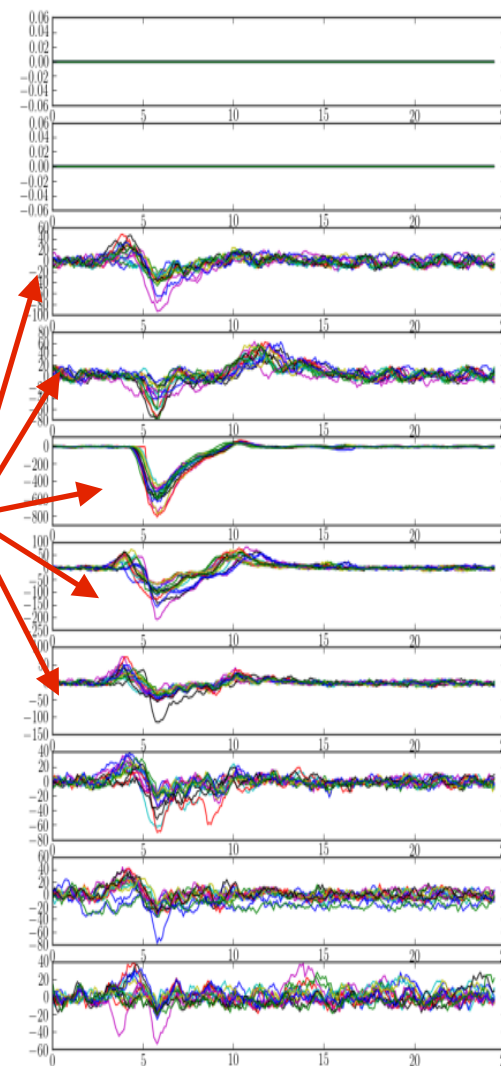
Right Side
Pulses on 10 striplines
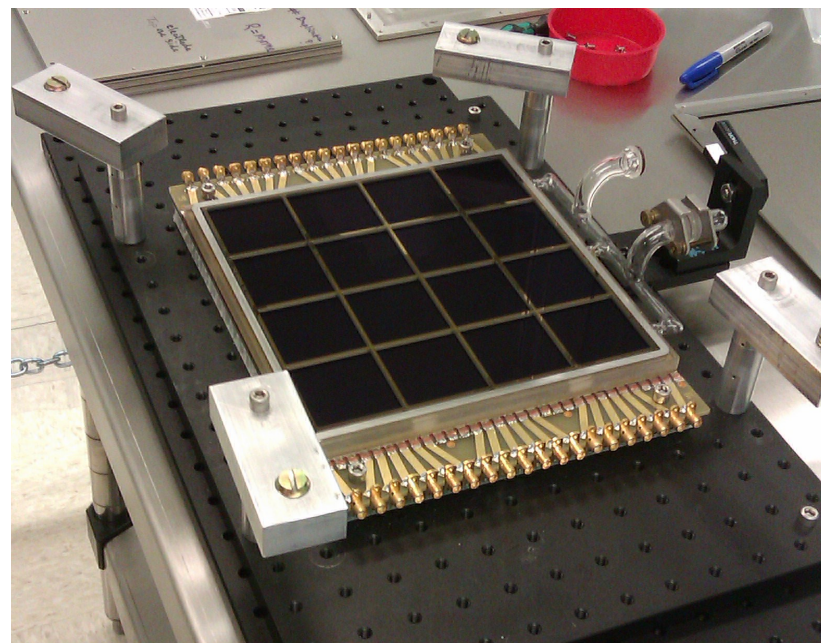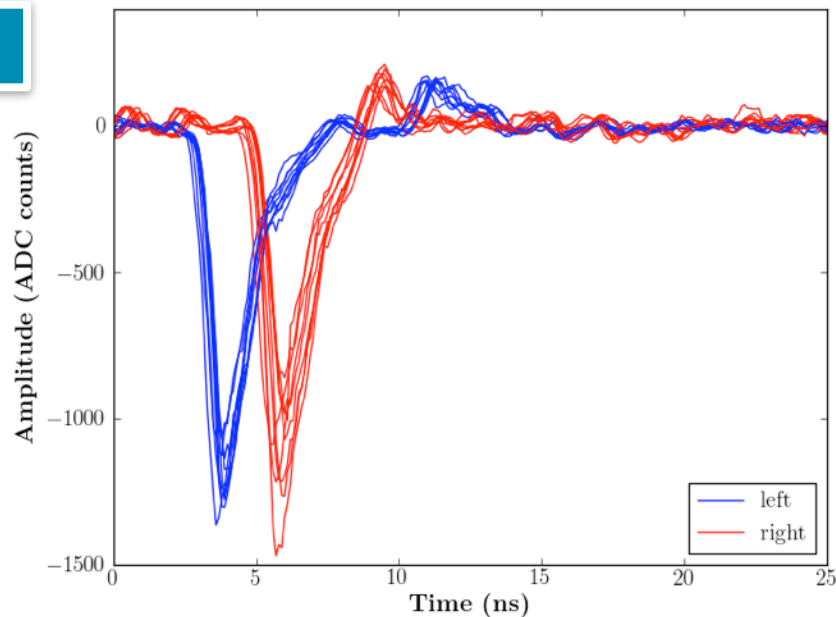
LAPPD

- LAPPD Goal of building a **complete detector system**, including even waveform sampling front-end electronics

- Now testing near-complete glass vacuum tubes ("demountable detectors") with resealable top window, robust aluminum photocathode
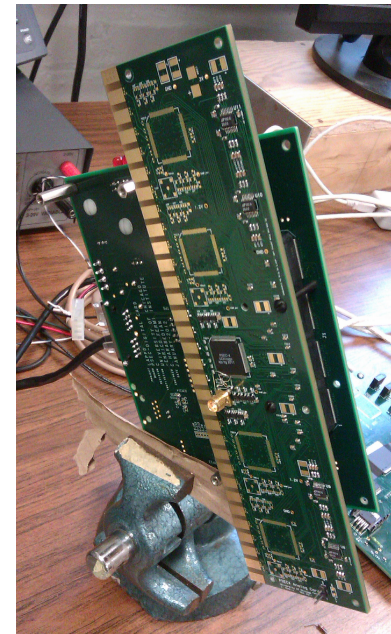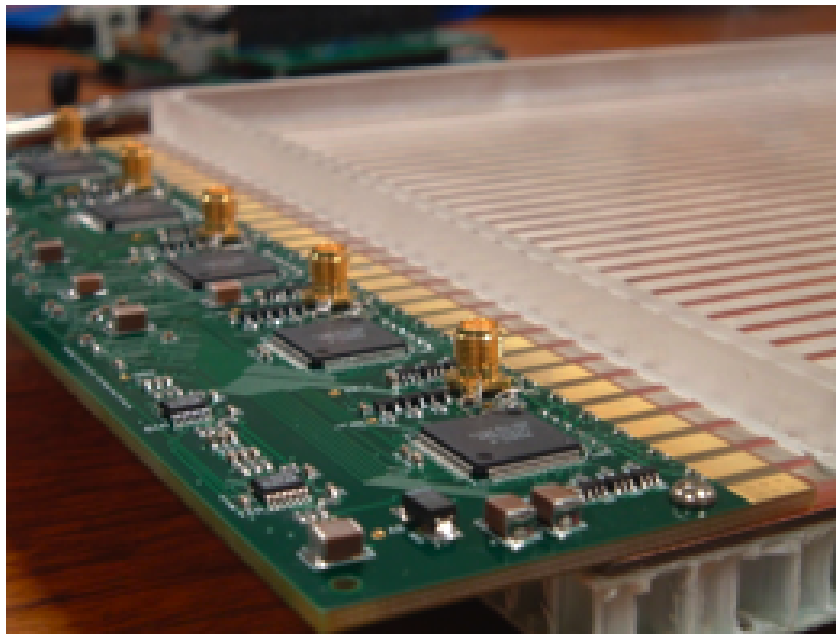
We are now testing a functional demountable detector with a complete 80 cm anode chain and full readout system ("SuMo slice").
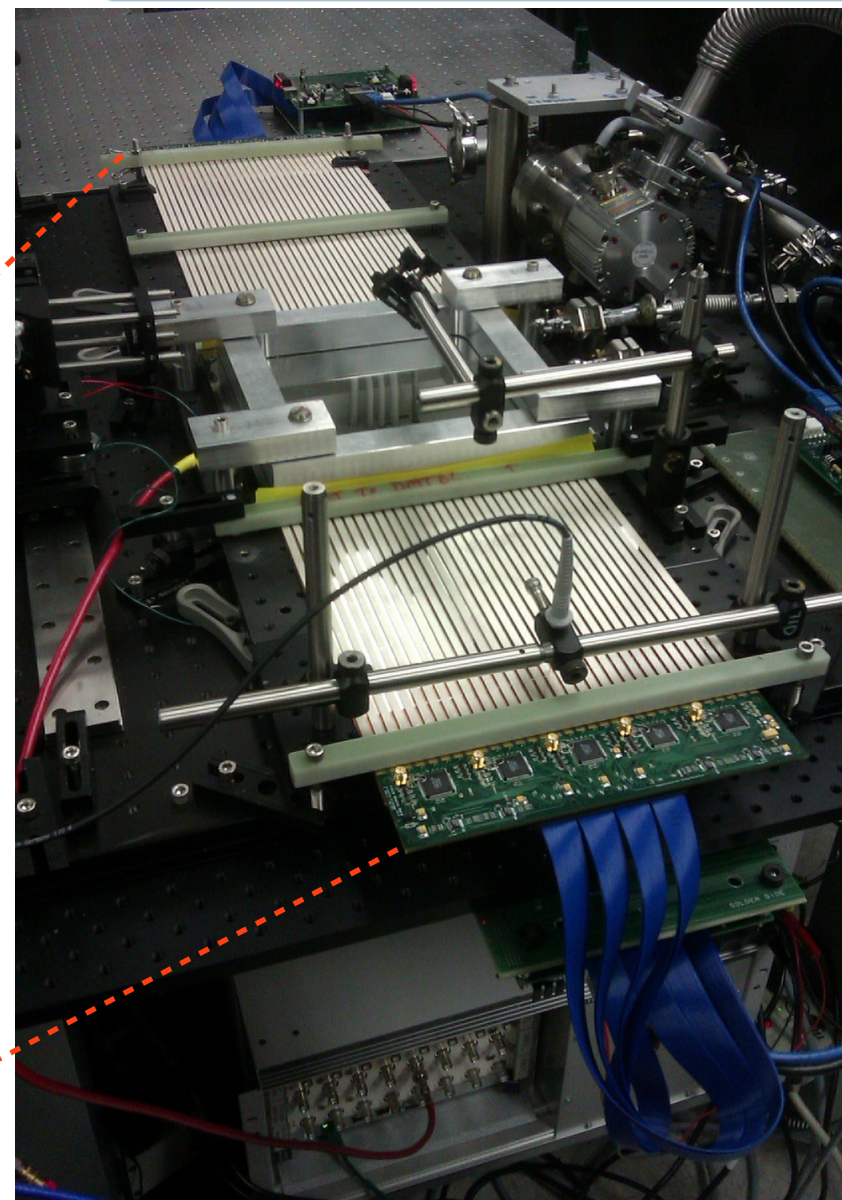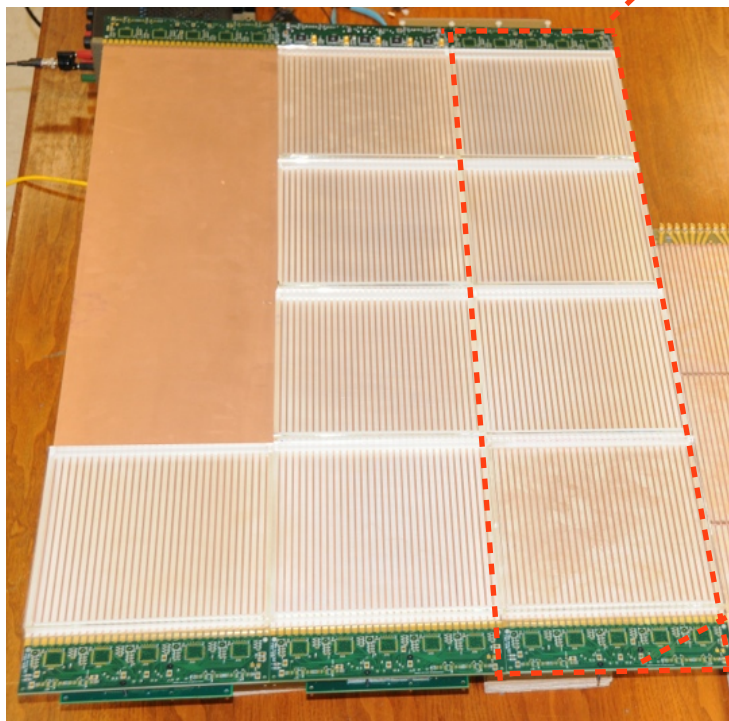
Psec4 chip:
- CMOS-based, waveform sampling chip
- 17 Gsamples/sec
- ~1 mV noise
- 6 channels/chip
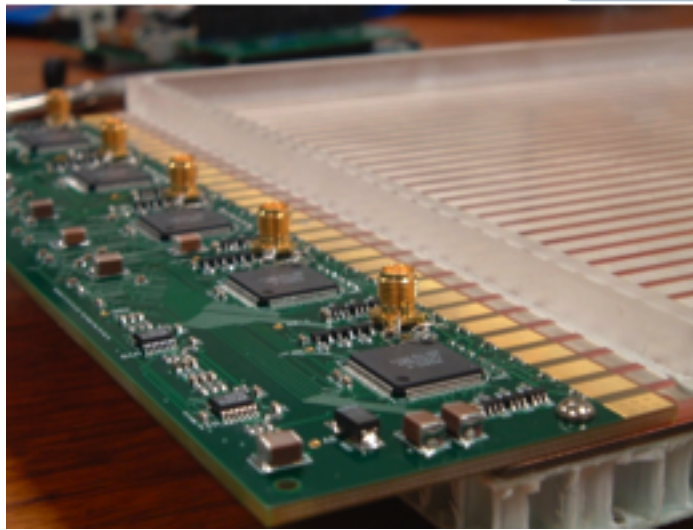
Analog Card:
- Readout for one side of 30-strip anode
- 5 psec chips per board
- Optimized for high analog bandwidth (>1 GHz)

Digital Card:
- Analysis of the individual pulses (charges and times)
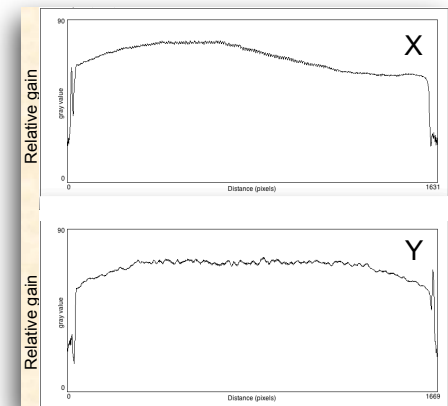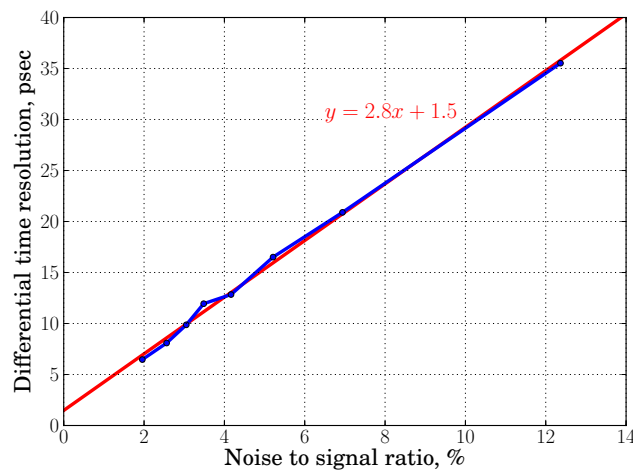
Central Card:
- Combines information from both ends of multiple striplines

LAPPD
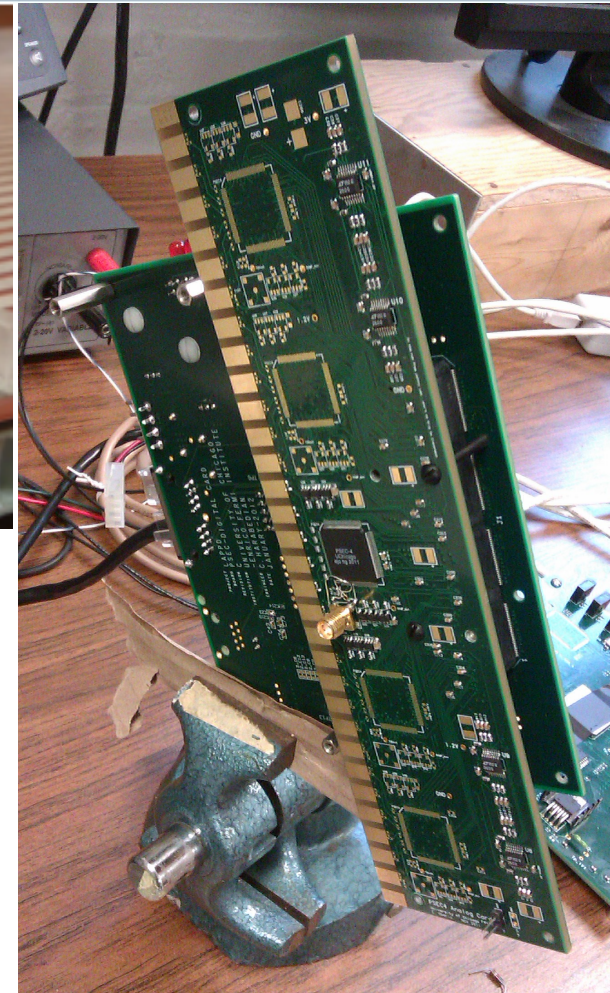
We observe:

- Typical gains of $O(10^7)$
- Single photoelectron time resolutions of ~40 picoseconds.
- Timing in the many-photoelectron limit approaching single picoseconds
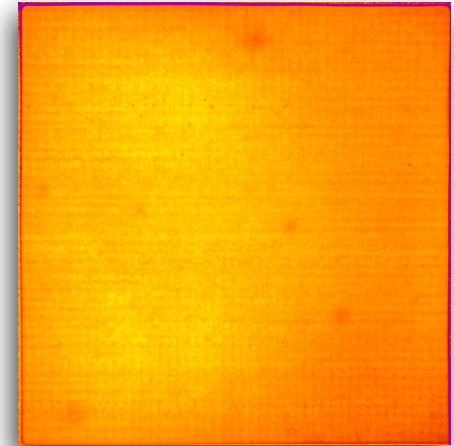
Berkeley SSL

ANL – MCP timing lab
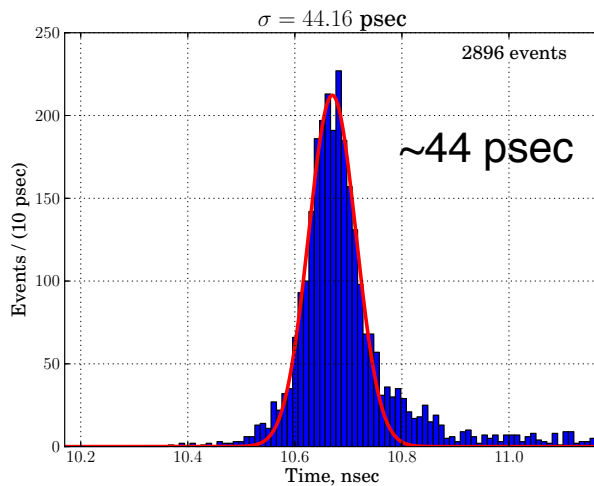
$\sigma = 44.16$ **psec**

2896 events

~44 psec

$y = 2.8x + 1.5$

Full Track Reconstruction: A TPC Using Optical Light?

1. Signal per unit length (before attenuation)

    ~20 photons/mm (Cherenkov)

2. "Drift time" (photon transit time)

    ~225,000mm/microsecond

3. Topology

    drift distances depend
    on track parameters
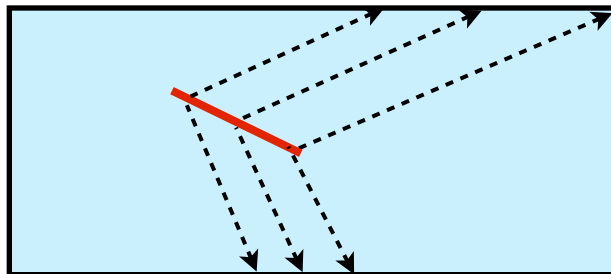
4. Optical Transport of light in water

Full Track Reconstruction: A TPC Using Optical Light?

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4. Optical Transport of light in water

Acceptance and coverage are important, especially at Low E. Is there any way we can boost this number? Scintillation? Chemical enhancement

This necessitates **fast** photodetection. It also requires **spatial resolution commensurate with the time resolution**.

This presents some reconstruction challenges, but not unconquerable.
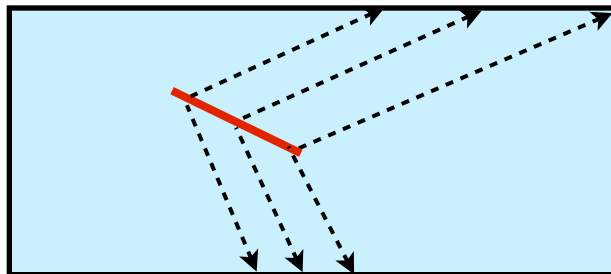
Appropriate reconstruction techniques are needed.

LAPPDs are essentially digital photon counters

- One can separate between photons based on spatial and time separation in a single photosensor (charge not even very necessary)
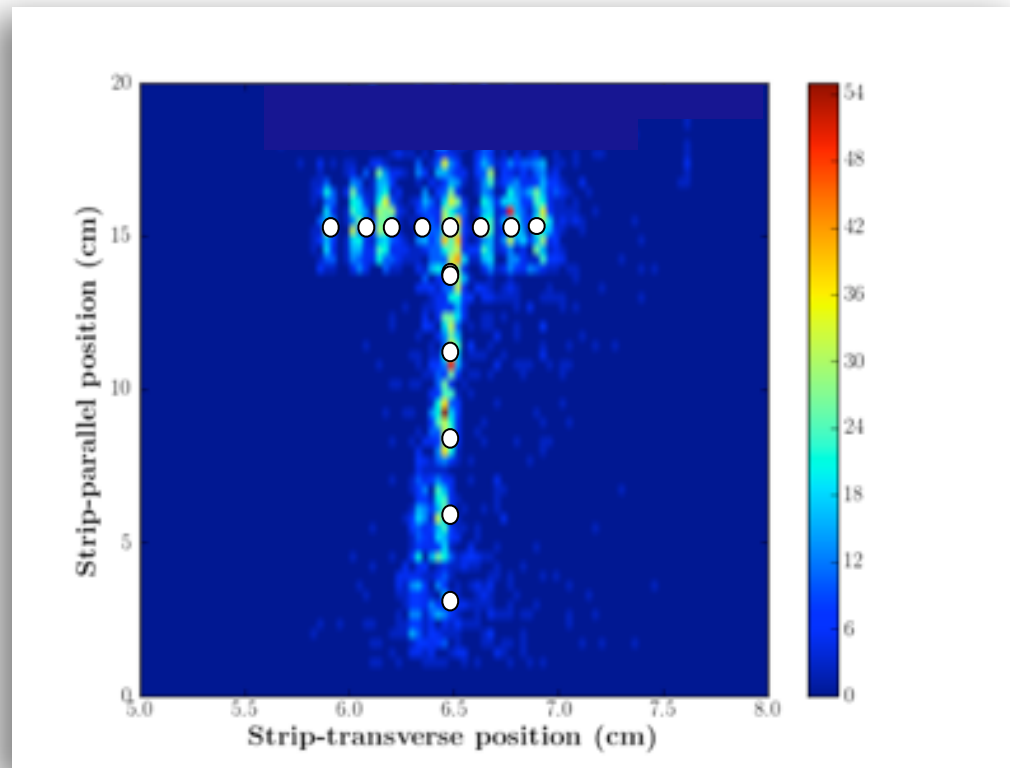
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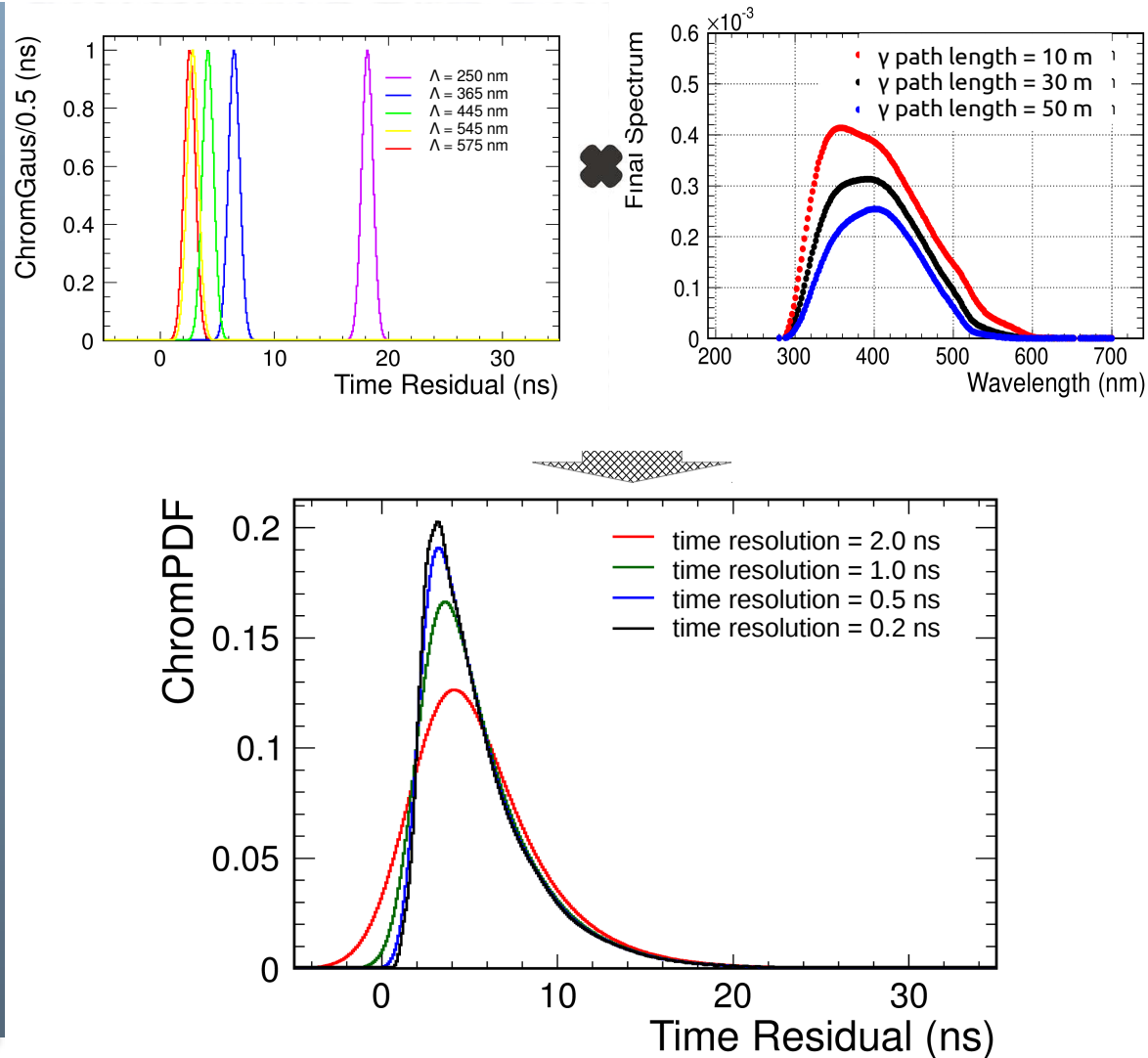
with conventional PMTs

- Measure a single time-of-first-light and a multi-PE blob of charge

- Likelihood is factorized into separate time and charge fits

- History of the individual photons is washed out

with hires imaging tubes

- Measure a 4-vector for each individual photon

- Likelihood based on simultaneous fit of space and time light

- one can separately test each photon for it's track of origin, color, production mechanism (Cherenkov vs scintillation) and propagation history (scattered vs direct)
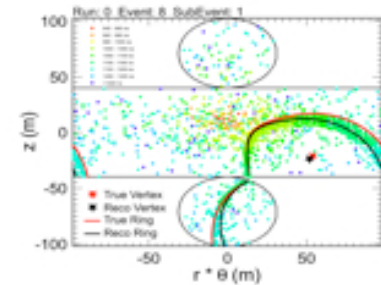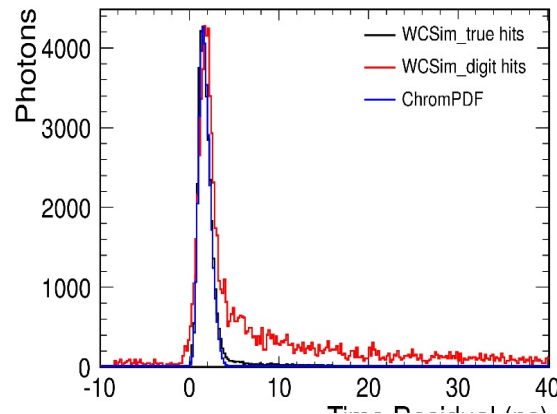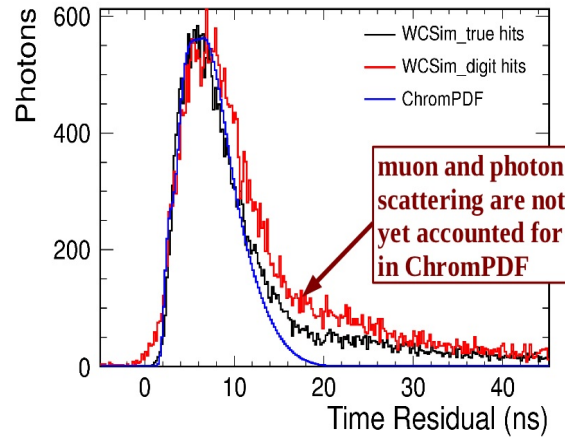
"Simple Vertex" Reconstruction

- A timing residual-based fit, assuming an extended track.
- Model accounts for effects of chromatic dispersion and scattering.
  - separately fit each photon hit with each color hypothesis, weighted by the relative probability of that color.
- For MCP-like photon detectors, we fit each photon rather than fitting (Q,t) for each PMT.
- Likelihood captures the full correlations between space and time of hits
- Not as sophisticated as full pattern-of-light fitting, but in local fits, all tracks and showers can be well-represented by simple line segments on a small enough scale.
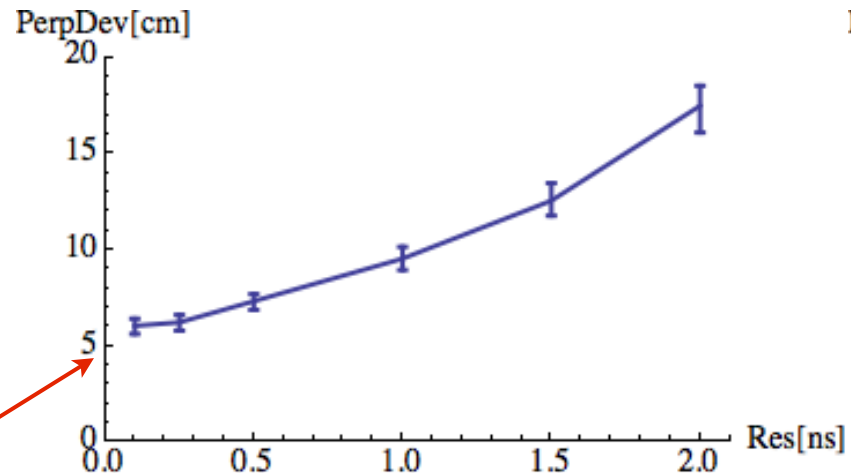

Work by I. Anghel, M. Sanchez, M Wetstein, T. Xin

"Simple Vertex" Reconstruction

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muon and photon scattering are not yet accounted for in ChromPDF

Work by I. Anghel, M. Sanchez, M Wetstein, T. Xin

Simple Vertex Reconstruction

- Transverse component of the vertex (wrt to track direction) is most sensitive to pure timing since T0 is unknown.

- Separating between multiple vertices depends on differential timing (T0 is irrelevant)

- We study the relationship between vertex sensitivity and time resolution using GeV muons in water. This study is performed using the former LBNE WC design, with 13% coverage and varying time resolution.

- Transverse vertex reconstruction is better than 5 cm for photosensor time resolutions below 500 picoseconds.

Optical TPCs are scalable to 100s of kilotons

~1 radiation length
~37 cm

vertices are separated:
at 7 degrees: ~4.5 cm
at 15 degrees: ~9.7 cm

Work by I. Anghel, M. Sanchez, M Wetstein, T. Xin

The isochron transform is a causal Hough Transform, that builds tracks from a pattern of hits in time and space.

$$\Delta t \approx s_1/c + s_2\, n/c$$
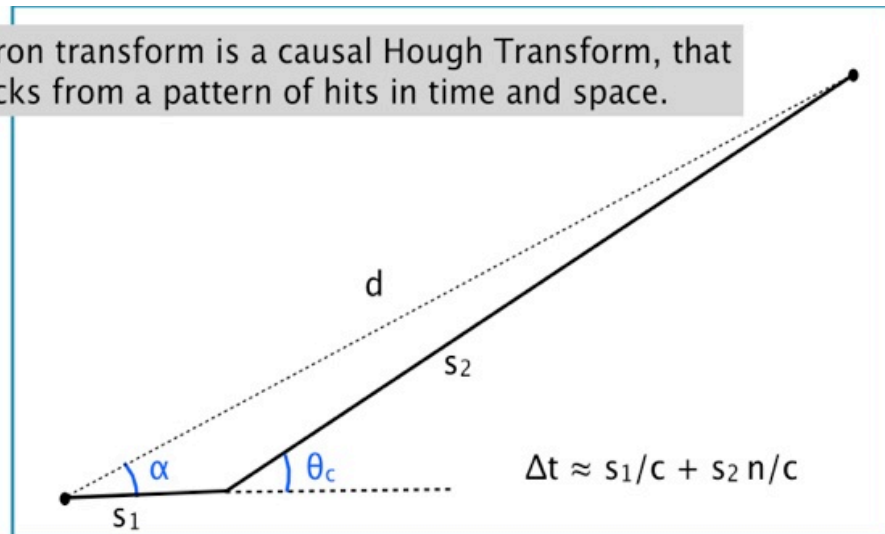
Connect each hit to the vertex, through a two segment path, one segment representing the path of the charged particle, the other path representing the emitted light. There are two unknowns:
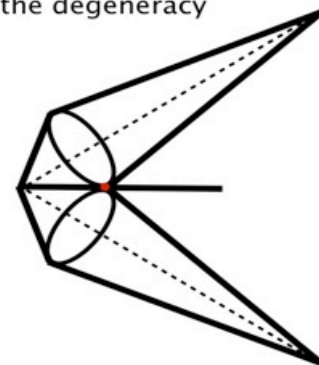
s_1 and α

but there are two constraints:

$$s_1 + s_1 = d \text{ and } \Delta t_{measured} = s_1/c + s_2\, n/c$$

For a single PMT, there is a rotational degeneracy (many solutions).
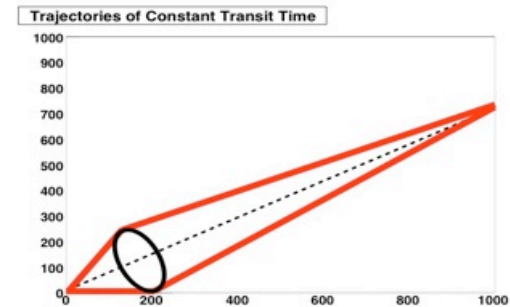
But, multiple hits from the same track will intersect maximally around their common emission point, resolving the degeneracy

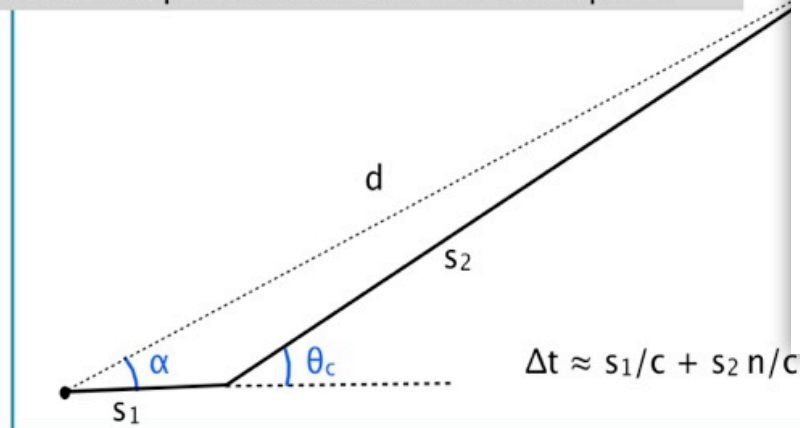M. Wetstein

first 2 radiation lengths of a 1.5 GeV $\pi^0 \rightarrow \gamma\ \gamma$

true

The isochron transform is a causal Hough Transform, that builds tracks from a pattern of hits in time and space.

d

s_2

α θ_c

s_1

$\Delta t \approx s_1/c + s_2\, n/c$

Connect each hit to the vertex, through a two segment path, one segment representing the path of the charged particle, the other path representing the emitted light. There are two unknowns:
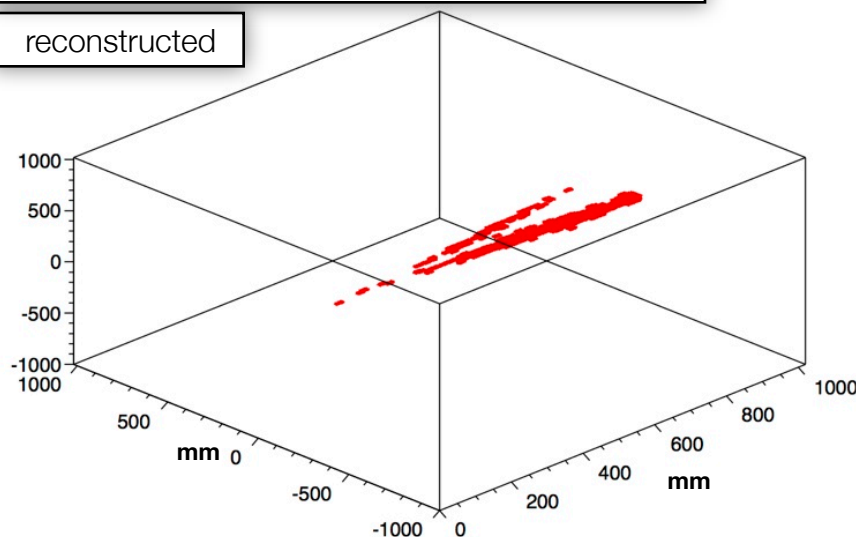
s_1 and α

but there are two constraints:

$s_1 + s_1 = d$ and $\Delta t_{measured} = s_1/c + s_2\, n/c$
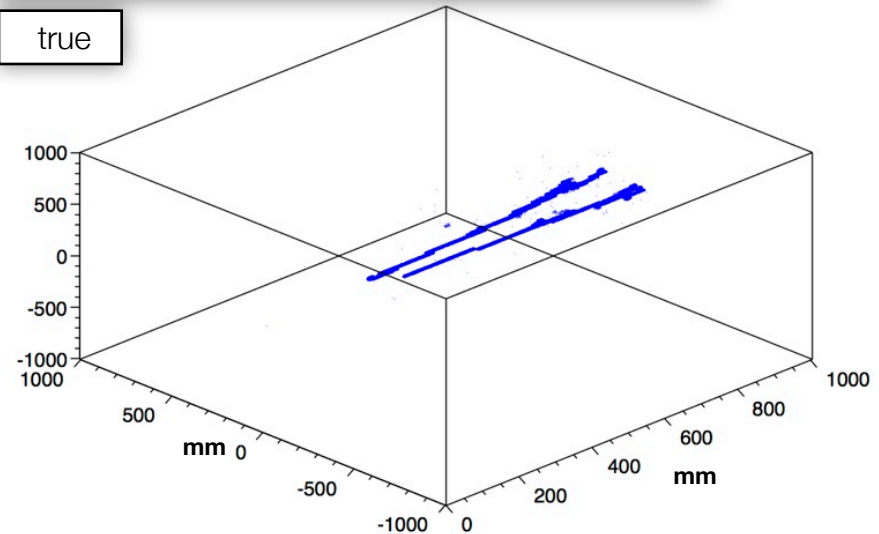
M. Wetstein

Isochron

first 2 radiation lengths of a 1.5 GeV $\pi^0 \rightarrow \gamma\ \gamma$

reconstructed

The isochron transform is a causal Hough Transform, that builds tracks from a pattern of hits in time and space.

$$\Delta t \approx s_1/c + s_2\, n/c$$

Connect each hit to the vertex, through a two segment path, one segment representing the path of the charged particle, the other path representing the emitted light. There are two unknowns:

  s_1 and α

but there are two constraints:

  $s_1 + s_1 = d$ and $\Delta t_{measured} = s_1/c + s_2\, n/c$

Could be useful for full pattern-fitting approached by providing a seed topology and restricting the phase space of the fit.

M. Wetstein

Reconstructed 750 MeV Pi0 (geant)
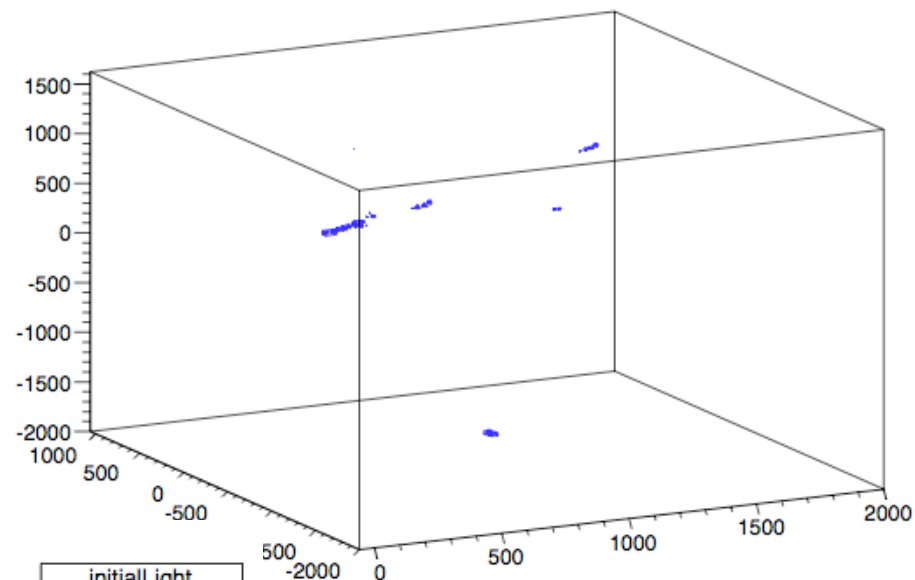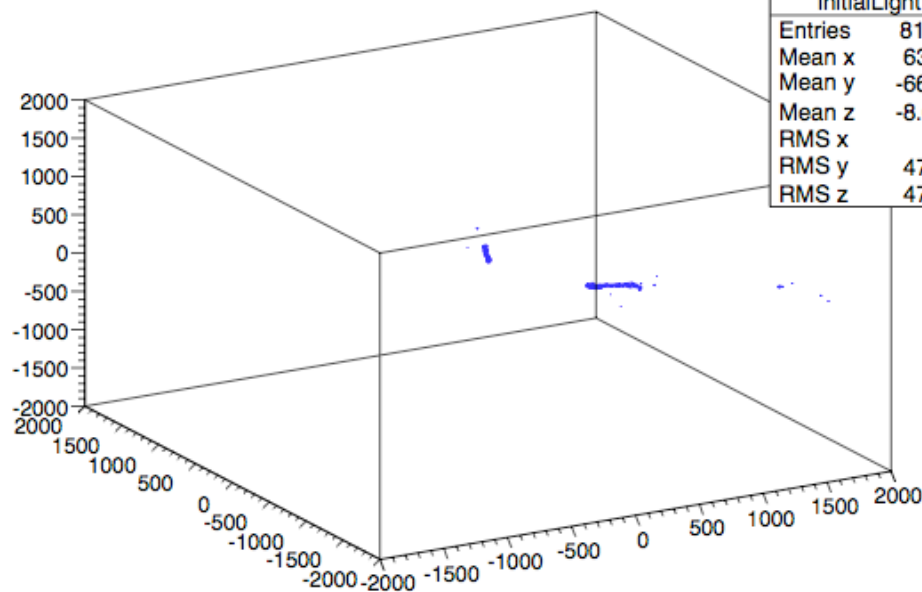

Reconstructed 750 MeV Pi0 (geant)
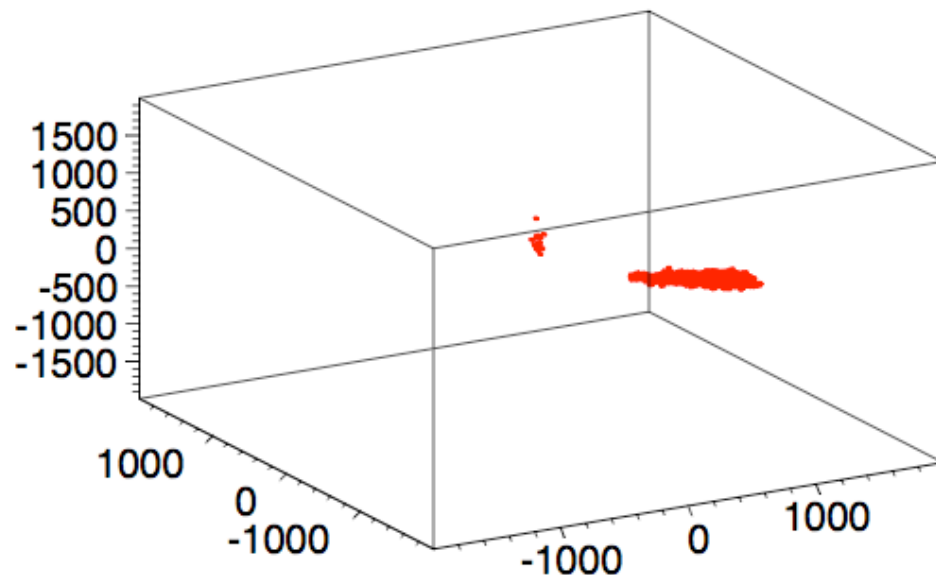
Comparing Isochron Reconstruction with Truth

True 750 MeV Pi0 (geant)
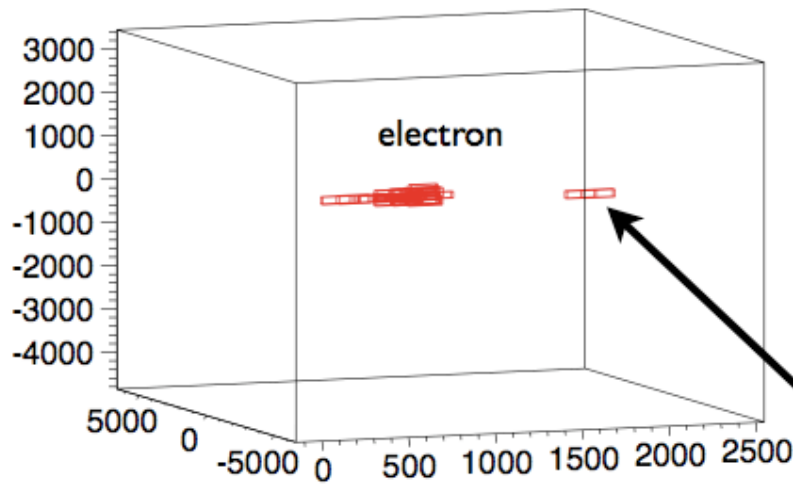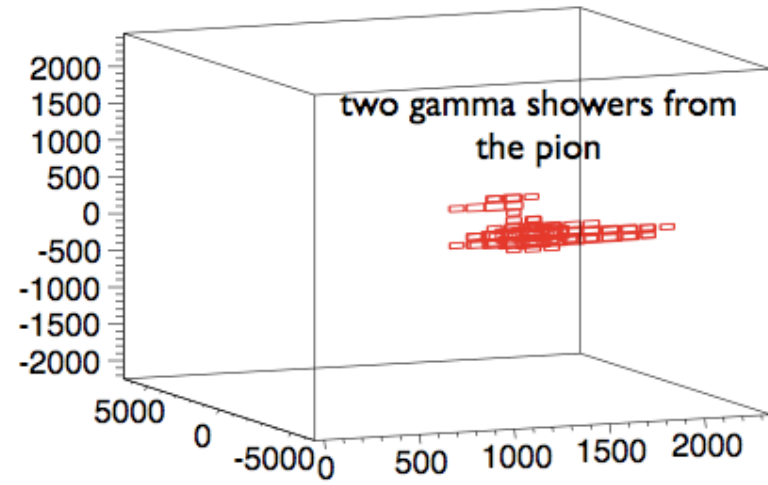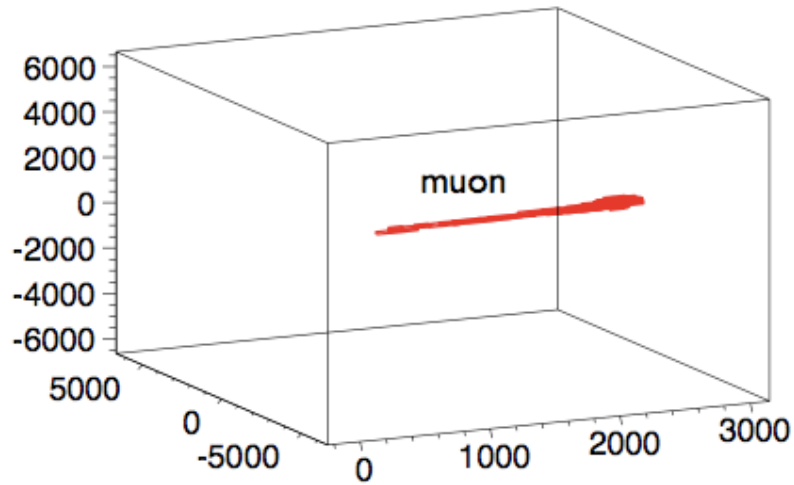
True 750 MeV Pi0 (geant)

| initialLight	
Entries	81301
Mean x	631.6
Mean y	-66.19
Mean z	-8.004
RMS x	319
RMS y	471.5
RMS z	47.52

Reconstructing Geant Events

muon

two gamma showers from the pion

electron

check out the detached shower from the bremstrahlung!!!

Optical TPC concept is more general than pure Cherenkov.

It may be possible to use timing to separate
between Cherenkov and scintillation light in liquid
scintillator volumes, capitalizing of the advantages
of each separately.

One can use the scintillation light for low E
sensitivity. <u>And the Cherenkov light for
directionality</u>.
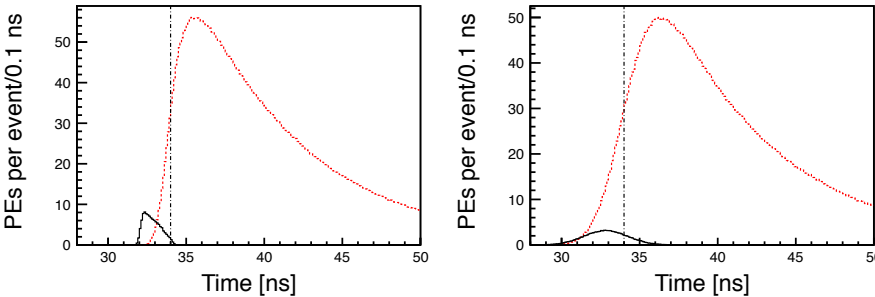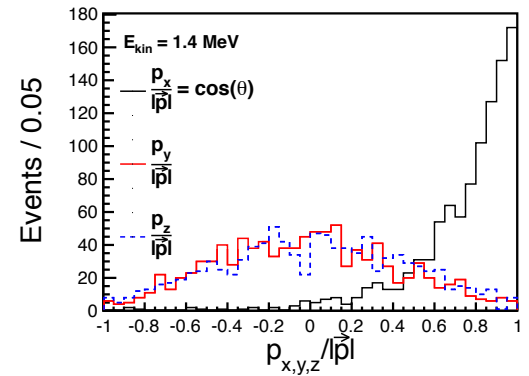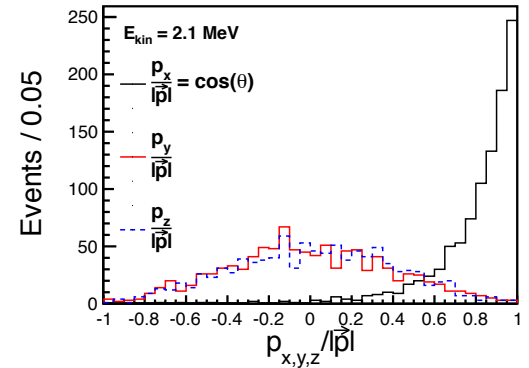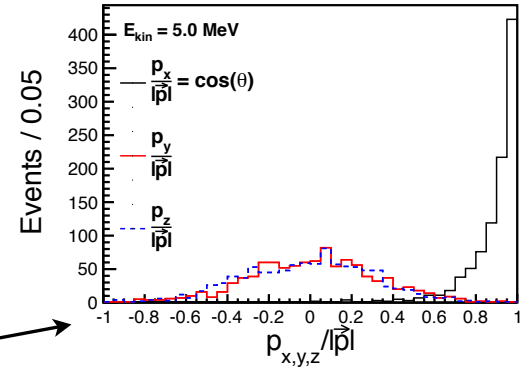
(a) Default simulation.

(b) Increased TTS (1.28 ns).
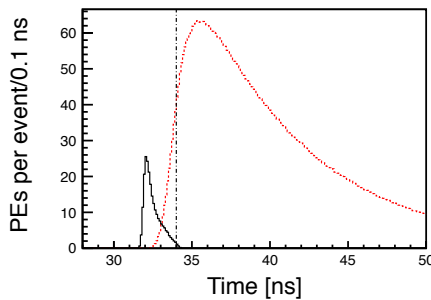
(c) Red-sensitive photocathode.

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Submitted to JINST, Nov. 2013. e-Print:
arXiv:1307.5813